Integrating aesthetic criteria with evolutionary processes in complex, free-form design – an initial investigation

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Abstract – **This research is a continuation of previous work by the authors relating to the inclusion of aesthetic criteria within an interactive evolutionary design system. The work described extends the design system re the manipulation of a more complex design problem with increased importance placed on aesthetic criterion. The paper initially introduces the previous work before describing more recent research and positioning this in terms of previously published work. Finally, initial results from the further developed design system are presented.**

I. INTRODUCTION

The following work relates to evolutionary interactive design systems which integrate machine-based evaluation of engineering and rule-based aesthetic criteria with the designer's subjective aesthetic evaluation of design solutions. Although much research relating to artificial design environments is evident [1, 2, 3] there is little evidence of the integration of evolutionary search and exploration, user evaluation (of design solutions) and machine learning within a single design environment [4]. Furthermore, integration of aesthetic criteria within computer-based design has been limited to the development of theoretical models with little evidence of application based research [5, 6].

A detailed discussion of factors which make such a system difficult to implement within a real world context can be found in Machwe et al [7]. Such factors have led to an approach commencing with a relatively simple system before slowly increasing the complexity of the problem. The research has led to a generic framework for an Interactive Evolutionary Design Environment (IEDE) as shown in (Figure 1).

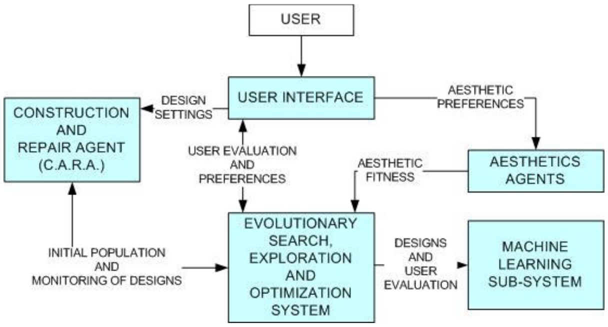

Figure 1. Interactive Evolutionary Design Environment.

This design environment has been developed for the experimental design of aesthetically pleasing, simply supported beam bridges.

Several novel concepts were introduced in this system. These include agent-based construction and repair of population members, Agent-based aesthetic evaluation, an object-based design representation supported by a case-based machine learning sub-system. The reader is directed to [4], [7] and [8] for a detailed description of the resulting interactive evolutionary design environment (IEDE).

Current work is extending the capabilities of the IEDE to handle greater complexity in terms of representation and aesthetic evaluation. Initial work related to simple bridge design whereas we are now considering the design of 'urban furniture' in the form of novel and aesthetically pleasing seating arrangements for parks and other public areas.

Simple structural analysis of the resulting forms is combined with both rule-based and user-led aesthetic evaluation at a more complex level than similar evaluation relating to the previous bridge structures.

II. BACKGROUND

The research can be considered a part of the Interactive Evolutionary Computing (IEC) field. Much work is evident in the IEC field e.g. Parmee [9,10], Carnahan and Dorris [11], Gero and Rosenmann [12], Takagi [13], Sims [14] to mention a few. Recent work in this field includes applications in the field of fashion design using a knowledge based encoding [15].

Parmee attempts to define various levels and types of interaction across a spectrum of IEC activity in [9] and [10]. Based upon this definition our current work lies towards the implicit end of this spectrum due to the combination of both quantitative, machine-based solution evaluation and user-led subjective evaluation.

We have extended support for the designer by integrating a machine learning sub-system to reduce designer fatigue [16]. This kind of support is essential since the user can only evaluate a limited number of solutions before fatigue takes over and consistency and quality of evaluation deteriorates. The machine learning sub-system uses a Case-based approach to store solutions ranked by the designer. The stored solutions

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are then used to evaluate future solutions which results in a reduction of the number of user-led evaluations to be made per generation.

III. REPRESENTATION

The work uses an object based representation as described in [7]. The representation is flexible in terms of the possible designs that it can represent but also robust enough to be used for design search, exploration and optimization. A single population member (chromosome) is a collection of primitive elements that represent a design. For example any structure made up of LEGO™ bricks can be represented as a collection of primitive design objects each with a specific x and y position and a pre-defined length (along X) and height (along Y). We also have the flexibility of using different elements with different design properties by just including them in the set of possible design primitives. When it comes to the evaluation of fitness of the structure and checking the structural integrity we use secondary properties of the particular primitive element type.

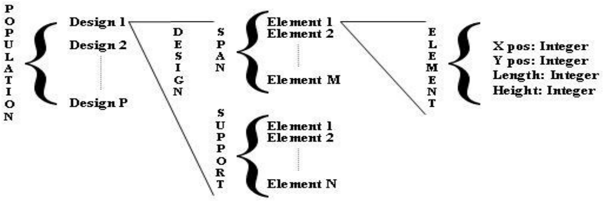

Figure 2. Representation for Bridge Design problem.

This representation was successfully used within a bridge design IEDE as described in [7]. As can be seen from Figure 2 the representation has been used for two dimensional designs (see Figure 3).

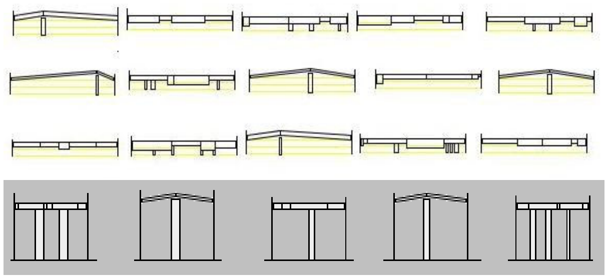

Figure 3. Some non-optimized/optimized bridge designs.

The present seating work requires an extension to three dimensions which has required some modification.. Figures 4 and 5 describe this extended representation.

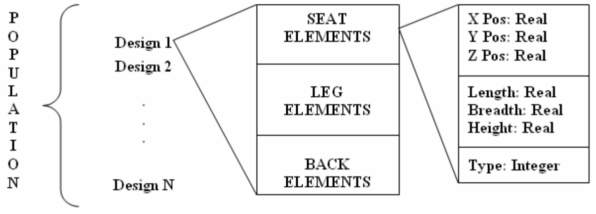

Figure 4. Representation of Benches

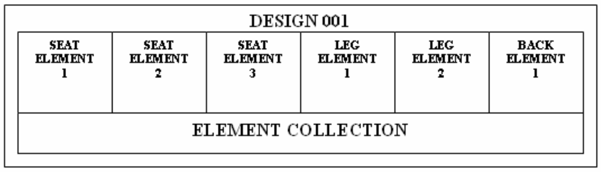

Figure 5. Basic structure of a Bench Solution

Instead of separating the elements into different collections as with the bridge work we have created three different kinds of element. These are the Seat, Back and Leg elements. All these are contained within a single collection.

An additional feature added within the new design representation is the concept of element design. Within the previous work all the elements were of the same design (basic cubic). In this case we have two kinds of elements namely a solid element and a 'grill' element. The basic difference between the two, other than the aesthetic-visual difference, is that a 'grill' element uses lesser materials and is lighter. Visual differences are also expected to play an important role in the designer's subjective evaluation of the solutions. These extensions, although simple at the moment, highlight the flexibility of a component based representation.. The two elements are illustrated in figures 6 and 7. It is apparent that many other element variations can be included as required.

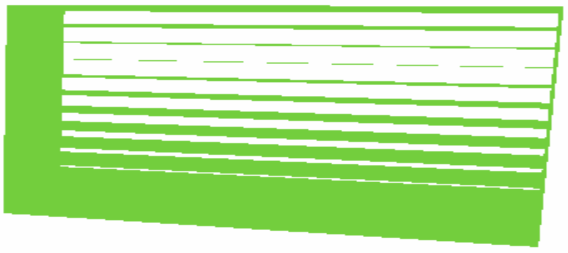

Figure 6. Grill Element.

Figure 7. Solid Element

A. *Increased Complexity of Representation*

In the bridge design problem the Span section elements contain four basic properties namely X and Y positions plus Length and Height]. The Seat element (analogous to the span element) contains six basic properties (X, Y, Z positions, Length, Breadth and Height). Similarly the Leg elements (analogous to Support Element) contains two extra properties (Z and Breadth). Thus a more complex design extending into the third dimension is now possible.

In terms of element for the bridge design, a Span element had a single degree of freedom (Height change) and the Support element had two degrees of freedom (X position and Length). In the bench design problem the Seat element has two degrees of freedom (Height and Length) similarly the Leg element has two degrees of freedom (Y position and Breadth).

IV. CONSTRUCTION AND REPAIR AGENTS (C.A.R.A)

As with the previous work we again use a Construction Agent (CA) to create the initial population. Due to the more flexible and complex nature of the representation the simple construction agent utilised in the bridge work is not viable. Furthermore the CA has been designed keeping in mind possible extensions to its functionality. These extensions include creation of a rule-based agent control interface.

It is common knowledge that gathering requirements is the first stage of any design process. Such an interface would allow us to take the first steps towards creating an agent-based, user-interactive ‘requirements gathering system’. This in turn could be extended into a generative system where the designer not only evaluates the solutions during a particular design cycle but also provides feedback to the CAs on the quality of solutions being generated. In the present work the rules for the CA have initially been kept simple. The rules define the number of Seat, Leg and Back elements to be created. Figure 8 further clarifies this idea.

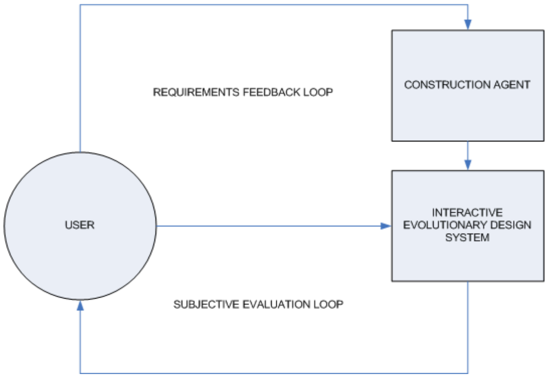

Figure 8. Basic Generative System.

A. *Mutation*

Mutation is rule-based. A major difference between the seating design problem and the bridge design system is that, due to the relatively less complex nature of the earlier work, only one element (irrespective of whether support or span type element) per design was mutated at one time. In the present work an element is selected from Seat and Leg type and mutated.

The mutation rules for Seat elements include the following:

1) Increasing Length (along X axis).
2) Decreasing Length (along X axis).
3) Increasing height (along Z axis).
4) Decreasing height (along Z axis).

Rules (1) and (2) result in a change in the Length parameter whereas rules (3) and (4) result in a change in the Height parameter. For the Leg elements the mutation rules include:

1) Moving Leg element left (along +ve Y axis).
2) Moving Leg element right (along –ve Y axis).
3) Increasing thickness of leg (along Y axis).
4) Decreasing thickness of leg (along Y axis).

Here Rules 1) and 2) result in a change in the Y position parameter and Rules 3) and 4) result in a change in the Width parameter. Figure 9 further clarifies the orientation of the axis and the various parameters.

As we are utlising EP where mutation is the only exploratory all solutions are subject to a single mutation.

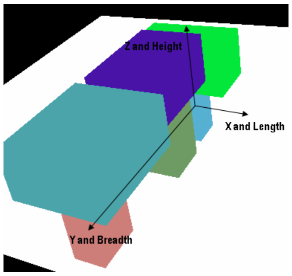

Figure 9. Orientation of Axis.

Another important change is the use of real values instead of integers. This allows us to obtain finer variation within the design through mutation by having real valued changes to the parameters.

Using such free form and simple rule based mutation requires a constant check of the population for damaged solutions. These include solutions with overlapping elements, elements floating in the air and badly formed elements. To facilitate this we have a Repair Agent which checks the validity of the mutation rule being used on a design. It ensures among other things that elements do not leave the bounding box for the design, are properly connected and are not badly formed (example: having negative dimensions). Without such a repair agent it would be difficult to use rule-based mutation whilst maintaining the efficiency of the algorithm.

V. EVOLUTIONARY ALGORITHM

Evolutionary programming (EP) [17] is a purely mutation based evolutionary algorithm which uses real number strings to represent solutions. Traditional EP also combines the parameters for mutation as part of the solution [18]. In all other aspects it is similar to a genetic algorithm (GA). The EP algorithm is shown below:

STEP 1: Randomly generate an initial population of P0 solutions and select fittest to form next generation P1.

STEP 2: Create C mutated solutions through random mutation from Pt.

STEP 3: Modify Pt by combining Pt and C populations. Thus Pt = Pt **U** C

STEP 4: From Pt select the Pt+1 best solutions to form the next generation.

STEP 5: If termination criteria met then STOP or else GOTO Step 2.

Thus the design representation is not restricted by the need to support crossover. The EP has been modified to work with a component -based representation and rule based mutation. This is achieved by using the Construction Agent to build solutions with the component-based representation and the Repair Agent to facilitate rule based mutation. Tournament selection is used as the primary exploitation operator.

VI. FITNESS FUNCTION

The present work uses a weighted sum fitness function. The fitness function is made up of five objectives which are combined into a single objective using weighted sum (weights can be changed by user at run time). The five objectives are:

1) Engineering Fitness.
2) Rule based Aesthetic Fitness
3) Cantilever Deflection Analysis.
4) Materials Usage
5) User Assigned Aesthetic Fitness.

A. Engineering Fitness

Engineering Fitness (E_Fit) consists of maximizing the buckling load for the seat supports and analyzing the seats for vertical deflection (treating it as a simple beam deflection problem with uniform loading). The formula used for calculating the buckling load is given in (1).

$$P' = \frac{\pi^2 EI}{H^2} \quad (1)$$

In (1) P' is the maximum load, H is the height of the leg, I is the moment of inertia and E is the Young's modulus. All values are in S.I. units. The simply supported beam equation is given by (2).

$$Y_{\max} = \frac{-0.01302\, wL^4}{EI} \quad (2)$$

Here Ymax is the maximum deflection (at the center of the beam span), E is the Young's modulus, L is the length of the seat, w is the weight per unit length of the uniform load and I is the moment of inertia of the beam cross section. The negative value of Y max signifies that the deflection is towards the negative of Y axis. All values are in S.I. units.

The buckling load difference (between actual load and maximum load supported) and the maximum deflection of seats are to be minimized. This is achieved using (3) which gives the value of E_Fit objective.

$$E\_FIT = \frac{1}{1 + BucklingLoad + BeamDeflection} \quad (3)$$

B. Rule Based Aesthetic Fitness

Rule based aesthetic fitness (A_Fit) uses the following rules to create uniform seat elements:

1) Seat elements should have uniform height.
2) Seat elements should have uniform lengths.

The higher the uniformity between the height and length of the seat element the higher is the aesthetic fitness. Uniformity is calculated through standard deviation of the dimensions. The higher the uniformity the lower should be the standard deviation of the dimensions across the different seat elements. Thus standard deviation must be minimized. (4) describes how A_Fit objective value is calculated.

$$A\_Fit = \frac{1}{1 + UniformBreadth + UniformHeight} \quad (4)$$

C. Cantilever Deflection Analysis

Cantilever deflection analysis (Cant_Fit) is required since if the leg elements are towards the center of the seat then the two ends of the seat will form cantilevers (fixed at supports) and must be analyzed for deflection.

$$Y_{\max} = \frac{PL^4}{8EI} \quad (5)$$

Equation 5 shows how cantilever deflection can be calculated when the load is towards the two edges (Figure 10). Within the formula Ymax is the maximum vertical deflection (at the edge), P is the load at the edge, L is the length of the cantilever beam, E is the Young's modulus and I the moment of inertia of the cross section of the beam. All values are in S.I. units. The objective is to minimize the vertical deflection. Equation 6 shows how Cant_fit value is obtained.

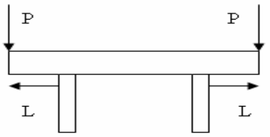

Figure 10. Cantilever Analysis

$$CANT\_FIT = \frac{1}{1 + CantileverDeflection} \quad (6)$$

The authors acknowledge the simplicity of the above structural analysis and recognise the need to analyse the structure as a continuous form. However, during the initial stages of the seating arrangement work we feel that a simple analysis is sufficient to provide a comparative evaluation of differing arrangements.

D. Materials Usage

Materials usage (Mat_Fit) calculates the amount of material used in the bench. This value is to be minimized. Equation 7 is used to obtain the value of Mat_Fit. The two different designs of seat element have different materials usage and thus have a deeper impact on the overall design than just at the subjective aesthetic level. The material currently envisaged for the bench design is steel with Young's modulus of around 190 GPa. Since a uniform material is evident the value of Young's modulus does not currently play a role within the system. However, future work will include material type as a variable across the elements resulting in mixed material structures where, for instance, the supporting elements are of a stiffer material and the seat elements are of a lighter material.

$$Mat\_Fit = \frac{1}{1 + MaterialsUsage} \quad (7)$$

E. User Assigned Fitness (U_fit)

At the end of a sequence which may comprise a single generation or any number of generations specified by the user the designer is presented with graphics of the top ten solutions with respect to the non-subjective criteria (A. to D.) and can grade the solutions from a scale of +1 to -1 (U_fit). The solutions which are better preferred by the user will tend to a score of +1. Thus the user can steer the evolution towards those designs which are found to be aesthetically pleasing.

F. Weighted Sum Fitness

Equation 8 shows how the objectives A thru E are combined to give a single fitness value for the design. In (8) W1 thru W5 are weights set by the user at run time. These weights are:

W1 = Weight for Rule based Aesthetic Fitness.
W2 = Weight for Engineering Fitness.
W3 = Weight for Materials Usage.
W4= Weight for User Assigned Fitness.
W5= Weight for Cantilever Deflection Analysis.

The weights can take a value between 0 and 3.

$$Fitness = w1A\_Fit + w2E\_Fit + w3Mat\_Fit + w4U\_Fit + w5Cant\_Fit \quad (8)$$

VII. RESULTS

It is only possible at this stage to show preliminary results but these do indicate that the various structural and aesthetic criteria are influencing the seating arrangement design.

The evolutionary programming algorithm being used for this study has a population size of either fifty or twenty depending upon whether user-assigned fitness has been included. Tournament selection with a tournament size of two individuals is performed at each generation to generate the next population of equal size.

A. Effects of the structural criteria.

Initial experimentation investigated the effect of the various structural criteria to assess there validity. To test the Cantilever deflection objective (CANT_FIT) the weights for all other objectives were set to zero and multiple runs were performed using a population size of fifty over twenty generations. The resulting structures showed supports situated at exteme ends of the seat (beam) i.e. a minimization of cantilever length was achieved. Best performance solutions contained both grillage and solid seat elements.

Investigation of the beam deflection of the seat elements as well as buckling in the leg elements (E_FIT) via multiple runs with the same population size and number of generations followed. When weights for all objectives excepting beam deflection and buckling are set to zero thick beam (seat) elements to resist deflection become evident in addition to large supports which almost cover the entire bench length i.e. a major reduction in deflection and buckling is achieved. Best performance solutions contained both grillage and solid seat elements.

Weights for all objectives excepting minimization of materials (MAT_FIT) were then set to zero and multiple runs with the same population size and number of generations followed. Emerging characteristics were: grillage seat elements rapidly became dominant; preferences for designs with one or two supports and a significant decrease in support cross-sectional area were evident.

All of the above indicated that the independent criteria were contributing in an appropriate manner.

B. Initial population characteristics

Eight members of an initial randomly generated population are shown in Figure 11 In this case all the five objective have been equally weighted. This gives an indication of the diversity present within the early generations. The seat elements are a mixture of grillage and solid forms.

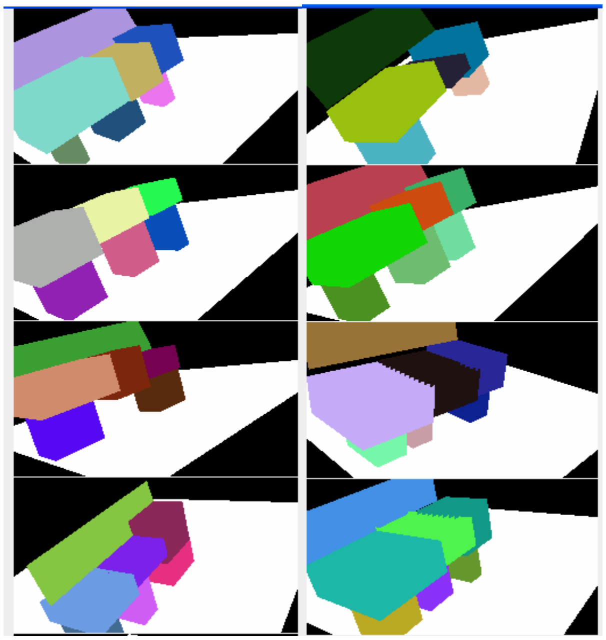

Figure 11. A sample of initial population members.

C. All Objectives at Equal Weights- No U_fit included

To provide a comparison between the effects of the more deterministic criteria and user-led subjective evaluation all objectives have equal weighting but user interaction has been excluded in this experiment. A population size of fifty individuals has again been utilised. After twenty generations well-supported structures are formed as shown in figure 12 where the best performance solution from four separate runs is shown. Some common trends are evident. For instance well-distributed supports for the seat elements; uniform lengths of seat elements and supports of similar cross-sectional dimensions. In all the seat elements the grillage structure has become the dominant form.

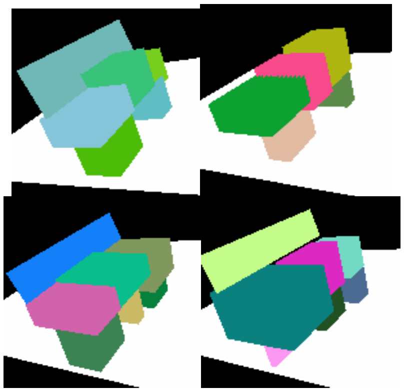

Figure 12. Solutions with all objectives at equal weight.

D. Including User-Assigned Fitness (U-fit)

Here all objectives except User-Assigned Fitness have a minimum weight of 0.5 (see (8)) whereas U_fit is assigned a weight of 3.0. The population size has been reduced from fifty to twenty individuals to both facilitate user-interaction and to better illustrate the manner in which the user can steer the evolutionary process during these initial experiments. Of the twenty solutions per generation the user evaluates the top ten performing solutions in terms of personal aesthetic preference.

Figure 13a shows the best performing solutions from the second generation. As would be expected there is a high degree of diversity in terms of the overall structures with varying numbers of supports at differing positions and differing seat element dimensions.

User aesthetic evaluation is introduced at each generation commencing at generation two and resulting in the structures illustrated in figure 13b. Convergence is achieved upon two distinct design options have emerged in the form of a single supported and twin supported arrangement.

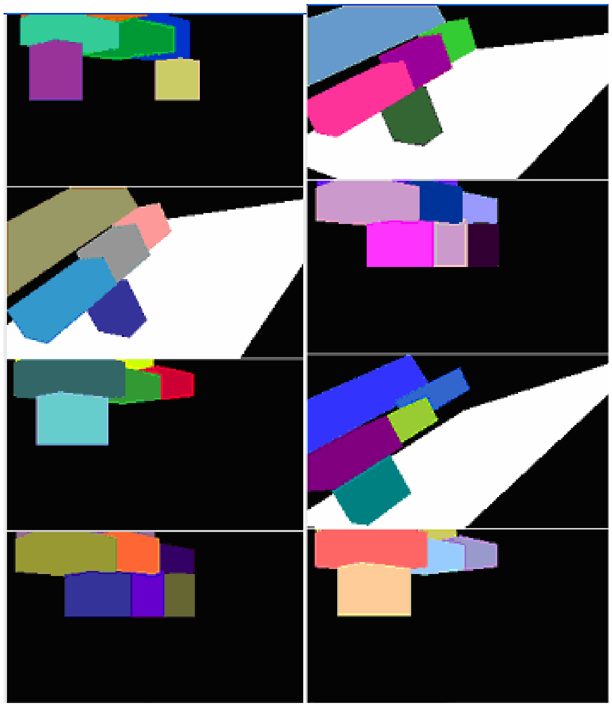

Figure 13a. Second Generation

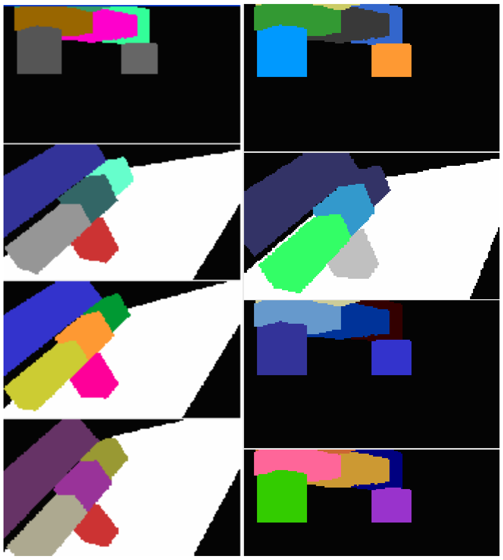

Figure 13b. Final Generation

It is apparent from figure 12 that these two arrangements would not have survived without the interaction of the user as the structures of figure 12 have very differing characteristics that have been largely defined by the structural criteria. Again, all seat elements in both cases are of the grillage type.

VIII. FUTURE DIRECTION

There is obviously major scope for significant further extension and improvement of the system. The intention is to enable the user-interactive evolution of novel, aesthetically pleasing seating arrangements for public places rather than the bench-like structures shown in the previous sections. However, it has been necessary to start from a relatively simple representation to establish initial proof of concept re the representation, machine-based criteria and the user-interactive considerations.

Figure 14 shows some examples of interactively evolved, highly free-form seating arrangements. These have been achieved through the introduction of less-restrictive CARA. rules and machine-based criteria relating to minimisation of the structures 'footprint' i.e. surface area covered by the structure. All the primary elements are the same as for the structures defined in the previous sections.

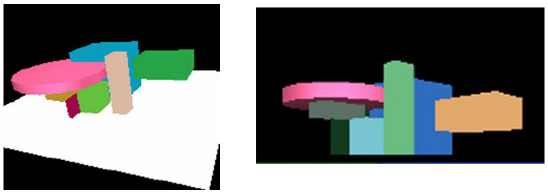

Figure 14. Free-form interactively evolved seating arrangements.

The principle problem with such free form designs is the difficulty relating to their structural analysis although these initial forms can be generated from user or rule based aesthetic judgement and other simple rule-based criteria. There is an argument, however, that during conceptual design the development of such forms under such criteria is entirely acceptable and that structural problems can be solved through the introduction of appropriate materials or via the introduction of skeletal frameworks at a later stage.

The intention is to develop the system so that concurrent evolution of the CARA rules is possible again through a user-interactive process. The system may commence with open ended rules for the CARA but with designer interaction these rules gradually become fixed.

The further development of the machine-based aesthetic assessment is essential. The more structured bridge design work included four aesthetic agents that managed rule-based criteria relating to symmetric positioning of supports; similarity in cross-sectional area of the supports; slenderness of the supports and slenderness ratio of the span elements. We have also developed an on-line case-based learning process for the bridge system which stores user-preferences enabling them to be utilised as machine-based criteria [16]. It is envisaged that this approach will be an essential aspect of the far-less structured seating arrangement system and work is progressing in this area.

Work has already progressed on the development of a more appropriate multi-objective representation to improve upon the initial weighted sum approach introduced here. An interesting utilisation of MOGA-type approaches relates to the possible measurement of the relative influence of user criteria [8]. This is an important aspect relating to the project as a whole as for such a complex system, cross validation of comparative effects of the various forms of evaluation is essential. We envisage something along the lines of the statistical analysis carried out by Carnahan and Dorris [11] in addition to the MOGA approach currently under development.

IX. CONCLUSIONS

Clearly, the extended system has greater complexity both in terms of possible designs being represented as well as the included criteria than the initial work involving the simple bridge structures. The extension of the structural criteria has been introduced and initial comparative experimentation has shown that such criteria are contributing in an appropriate manner.

Comparative experimentation has provided an indication of the contribution of user aesthetic evaluation over and above the machine-based structural criteria.

It is always difficult with interactive evolutionary computing research to rigorously investigate the dynamics of the machine-based / user-led components due to the time and fatigue elements associated with multiple runs and associated user involvement. The objective of the above work, however, was to merely establish a proof-of-concept relating to the feasibility of the approach as opposed to a rigorous analysis. It is the opinion of the team that such a proof-of-concept has been achieved via the work described.

Hence, the work described can now provide a platform for the development of a more realistic and meaningful system.

REFERENCES

[1] Gero, JS (2002) Computational models of creative designing based on situated cognition, in T Hewett and T Kavanagh (eds), Creativity and Cognition 2002, New York, ACM Press, USA.

[2] Bentley, P.J. ed. (1999). Evolutionary Design By Computers. 1st Edition. Morgan-Kaufmann, USA.

[3] Parmee I. C (2001) Adaptive and evolutionary computing in engineering design. Springer Verlag.

[4] Machwe, A. Parmee, I.C. and Miles, J.C. (2005) Integrating Aesthetic Criteria with a user-centric evolutionary system via a component based design representation. Proceedings of International Conference on Engineering Design (2005), Melbourne, Australia.

[5] Moore C. J., Miles J. C., Evans S. J., (1996) "Innovative Computational Support in Bridge Aesthetics", Transp. Res Record, 1549, 1-11.

[6] Saunders, R. (2001) Curious Design Agents and Artificial Creativity, Ph.D. Thesis (Electronic Edition), Faculty of Architecture, The University of Sydney.

[7] Machwe, A. Parmee, I.C. and Miles, J.C. Overcoming representation issues when including aesthetic criteria in evolutionary design. Proceedings of ASCE International Conference in Civil Engineering(2005) ,Mexico.

[8] Machwe, A. Parmee, I.C. and Miles, J. C. (2006) Multi-objective analysis of a component based representation within an interactive evolutionary design system. Adaptive Computation in Design and Manufacture 2006, Bristol, UK

[9] Parmee, I.C. (2002). "Improving problem definition through interactive evolutionary computation". Artificial Intelligence for Engineering Design, Analysis and Manufacturing (2002), 16(3), pg. 185-202. Cambridge University Press, Printed in USA.

[10] Parmee I.C. and Abraham J. A. R., (2005), Interactive Evolutionary Design. In: Y. Jin (Ed), Knowledge Incorporation in Evolutionary Computation, Springer Verlag..

[11] Carnahan, B. and Dorris, N. (2004) Identifying Relevant Symbol Design Criteria Using Interactive Evolutionary Computation, Genetic and Evolutionary Computing Conference (GECCO) 2004, Seattle, USA.

[12] Rosenman, M. and Gero, J. (1999). Evolving Designs by generating useful complex gene structures, in Bently, P.J. (ed). Evolutionary Design by Computers, Morgan Kaufmann, San Fransisco.

[13] Takagi H (1998), Interactive Evolutionary Computation: Cooperation of Computational Intelligence and Human KANSEI. Proceedings of 5th International Conference on Soft Computing and Information/Intelligent Systems (IIZUKA 1998), Japan

[14] Sims, K. (1994). Evolving Virtual Creatures. Computer Graphics Proceedings.

[15] Hee-Su Kim and Sung-Bae Cho (2005) Fashion Design using Interactive Genetic Algorithm with Knowledge-based Encoding. In: Y. Jin (Ed), Knowledge Incorporation in Evolutionary Computation, Springer Verlag..

[16] Machwe, A. and Parmee, I.C. (2006) Introducing Machine Learning within an Interactive Evolutionary Design Environment. International Design Conference – Design 2006, Croatia..

[17] Fogel, D.B. (1988). An Evolutionary approach to the travelling salesman problem. Biological Cybernetics 60(2), 139-144.

[18] Deb, K. (2001). Multi-objective Optimization using Evolutionary Algorithms, John Wiley and Sons.