INTERACTIVE VISUALISATION SYSTEMS FOR CONCEPTUAL BUILDING DESIGN: A PRACTICAL APPROACH

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Abstract

At the conceptual stage of the design process where only a partial specification for a design is available and due to fuzzy nature of information at this stage it is difficult to program every design requirements. Experience has shown that evolutionary computation EC, (particularly the genetic algorithm) to be an effective decision support tool for conceptual design. To make EC useful in this stage of the design it needs strong human interaction and guidance to lead the search in discrete regions of the search space to explore and discover more appropriate design concepts. Humans are extremely good at perceptual evaluation of designs according to criteria that are extremely hard to program (Eckert et al., 1999). As a result, they can provide useful fitness evaluation for interactive evolutionary systems. They can also include personal preferences to lead the search and exploration to a preferred direction. This kind of interaction is extremely important to satisfy design/client requirements, particularly at the conceptual stage of the design process. This paper introduces a novel approach which demonstrates that interactive use of evolutionary computation, assisted by visualisation tools, leads to a human-led search. A system which support human-led search and it is based on an interactive visualisation clustered genetic algorithm, developed by Packham and co-workers (Packham, 2003; Packham and Denham, 2003; Packham et al., 2004; Rafiq et al., 2004), is introduced and its application on an example of a multi-disciplinary decision making process is demonstrated.

Introduction

For over a decade not only have techniques from the field of Evolutionary Computation, EC (particularly the Genetic Algorithm, GA), played a major role in design optimisation, but they are also seen as an analogy of design methodologies (Gero et al., 1997). More recently their role has been recognised as support tool for conceptual design (Goldberg, 2002).

The GA is typically a knowledge lean search process, and while this can be seen as one of its major strengths thus providing it with its wide applicability; it can be a hindrance when attempting to incorporate the richness of human knowledge, experience and insight into the search process.

This is particularly exemplified at the conceptual stage of the design process where: Firstly, only a partial specification for a design is available and due to fuzzy nature of information at this stage it is difficult to program every design requirements. It is argued that EC approaches need strong human interaction and guidance to lead the search in discrete regions of the search space to explore and discover more appropriate design concepts; Secondly due to the ill-defined nature of requirements the process itself is not one of search, but rather an exploration of the requirements and the potential solutions to those requirements (Gero, 1993; Maher et al., 1995).

However, with an ancestry in the artistic creations of Dawkins (1986) a new field of Interactive Evolutionary Computing (IEC) has begun to emerge and has been adapted to meet to a wide spectrum of application areas (Takagi, 2001).

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The authors believe that human-led IEC visualisation tools assisted by the search and exploration power of EC could be a powerful tool for human designers. To this end, the next section, discusses and presents a broad categorisation of visualisation and human iteration approaches adopted in EC systems. More detailed examples of visual and interactive systems as applied to conceptual building design will follow. Finally the paper will describe research on the Interactive and Visualisation and Clustering Genetic Algorithm (IVCGA).

Visual and Interactive Evolutionary Systems

Different approaches have been used to visualise the results of the EC search, and to make the EC process more interactive and user friendly. Lately research, discussed in this section, has been extended to allow users to interact with the evolutionary system to direct search in order to explore regions that are potentially more interesting.

The aim of this section is to discuss and review both the involvement of visualisation techniques for GA search, and the categories of interactive GA systems. Finally the major attributes of a visual interactive GA are discussed, and how such systems play a role in human led design.

Interactive Evolutionary Computation

Interactive Evolutionary Computation (IEC) is an umbrella term covering a range of techniques where the user interacts with the Evolutionary Computation search process to direct or modify the search based upon subjective preferences.

In a review of IEC, Takagi (2001) presents two definitions corresponding to a *narrow* and a *broad* view: In the narrow view IEC is seen as “the technology that EC optimises the target system based upon subjective human evaluation as fitness values for system outputs” (Takagi, 2001, p. 1275). This narrow view is more traditionally referred to as Interactive Genetic Algorithms (IGA). On the other hand, the broad definition is seen as “the technology that EC optimises the target system having an interactive human-machine interface” (Takagi, 2001, p. 1275), where the user modifies the GA parameters. A similar, but slightly broader, categorisation of IEC is also made by Parmee (2002).

In the IGA the user effectively replaces the fitness function. The classical example of this is the Biomorhps of Dawkins (1986), in this instance the user is presented with images of a series of candidate designs and selects a subset for reproduction. Their usage is normally in situations where it is not possible to provide a quantifiable fitness function, i.e. in the case of evaluating designing for their aesthetic content.

The approach adopted by IGA’s has been successfully applied across a range of domains: Graphic art (e.g. Unemi, 2000; Todd and Latham, 1999); Industrial design (e.g. Graf, 1995); Face image generation (e.g. Takagi and Kishi, 1999); Speech processing (e.g. Watanabe and Takagi, 1995); Geological modelling (Wijns et al., 2003). The reader is referred to Takagi (2001) and Banzhaf (1997) for a more comprehensive review of applications.

While the IGA has only found limited usage in conceptual building design (Buelow 2002), it has been argued that such systems have a major role during conceptual design and “can fit naturally into human design thinking and industrial design practice” (Eckert et al., 1999).

Despite the obvious success of this approach it does suffer shortcomings, one of these being human fatigue. In a typical EC search the population size is usually one hundred and may evolve for a considerable number of generations. Human evaluation of this large number of individuals leads to not only inevitable fatigue, but also it is cognitively difficult for humans to rank or choose between this number of individual concepts generated by the system.

One approach to this problem is to use smaller population sizes across fewer generations. On more complex design problems with high dimensional search spaces a small population size may not cover the search space adequately but also exhibits rapid convergence.

To overcome the small population size issue, predictive evaluation techniques can be adopted. Here the user assigns a fitness score to a few selected individuals and the IGA predicts the fitness of the remaining individuals. This prediction can be either based on machine learning techniques (i.e. Neural Networks, Biles et al. 1996), or a Euclidian based similarity measure. The difficulty with Euclidian techniques is to develop a scale which mirrors the human evaluation scale.

The IGA may only have a limited role to play as an exploratory design tool in its fullest sense. If EC approaches are used as exploratory tools then it is necessary to allow the user to explore, or to move the search to, differing areas of the solution space which the user (i.e. expert designer) finds particularly interesting or due to a different emphasis on particular design requirements, and to have the ability to return to those areas for later investigation.

Currently it would seem that while IGA's are very effective in allowing a user to guide the search through the solution spaces, they do not readily allow the re-visiting of particular choice points. This ability to move the search, or focus at a specific region, is particularly important during conceptual design where the actual requirements themselves are being re-defined through the exploration process.

When the broader definition of Takagi (2001) is considered, again variants can be identified. One approach which uses human interaction in its fullest sense is the Human Based Genetic Algorithm (HBGA) of Kosorukoff (2001) and Kosorukoff and Goldberg (2002). The HBGA extends the IGA approach of the user driven selection, by allowing the user the option to perform and modify the GA operations of crossover and mutation. With the motivation that humans prefer to be creators rather than critics, in essence the evolutionary search process is now guided by human innovation. Moreover the HBGA is seen as a key member in collaborative problem solving and is playing a major role in the Free Knowledge Exchange (FKE) project and the DISCUS[1] project of Goldberg et al. (2003).

An alternative, and more traditional, approach is where the user is allowed to set or to modify GA parameters. Thus the work of Parmee et al. (2000) allows the user to set design objective preferences at the start of the GA search process, whilst the work of Mathews and Rafiq (Mathews, 2000; Rafiq et al., 2003; Rafiq et al., 2001) allows user modification of GA parameters during the GA run.

Visualising Evolutionary Computation

In terms of visualisation three main approaches can be identified: Firstly, tracing the ancestry of the evolving individuals or representing the genetic composition of individuals (Collins, 2002; Hart and Ross, 2001; Smith et al., 2002). The information presented in this approach is of interest to researches in Evolutionary Computation, rather than designers or users of such systems.

Secondly, the simplest attempt to introduce visualisation to help designers was that of a simple fitness plot and later on interaction with the fitness plot to backtrack the evolution process (Mathew, 2000), and in the multi-objective case, plotting the Pareto front or Pareto surface (Grierson and Khajehpour, 2002), puts this technique to good effect.

Thirdly, in high dimensional spaces it is difficult for the designer to see relationship between the design variables or the interaction with the objectives. The work of Abraham and Parmee (2004) uses a box-plot technique to display design variable – objective interaction, whilst Hayashida and Takagi (2000) used techniques to map high dimensional spaces to a 2-D mapped space.

[1] DISCUS: Distributed Innovation and Scalable Collaborations in Uncertain Settings.

In all cases discussed so far, visualisation is performed during or after the GA run has terminated and the user is not able to interact with the system either to refine the search or to move the search to a different area of the search space.

Closing Comments

This section discussed the ideas of interaction and visualisation as separate concepts and attempted a categorisation of each. In the following section a number of examples of illustrating how these concepts have been applied to Engineering Design problems are presented.

Following this, we present details of a unique approach which combines interaction and visualisation, the Interactive Visualisation and Clustering GA (IVCGA) developed by Packham et al (Packam, 2003; Packham and Denham, 2003; Packham et al., 2004; Rafiq et al., 2004)

Examples of Interactive and Visualisation Systems for Engineering Design

A comprehensive review by (Takagi 2001) lists a number of approaches to and applications of the IEC.

One of the first preliminary design systems devised by Pham and Yang (1993) allowed the user to view and evaluate solutions produced by the GA. Jo (1998) discovered that adding human interaction to his evolutionary design system allows domain knowledge to be incorporated online; solutions can be independently visualized in a space layout problem and the user was able to modify individual elements of the design. The interaction of a user has also been considered in a multi-objective environment: Fonesca and Fleming (1993) proposed a decision-maker (DM) that controls which objectives have more importance within a non-dominated set of solutions. They suggested the DM could be a human or an expert system. Horn (1997) pointed out that there are three different approaches to decision making in multi-criteria problems: make a multi-criteria decision before search, make a decision after search or integrate the search and decision making. The latter approach would appear to be the most powerful, incorporating iterative search and decision making.

Mathews and Rafiq (Mathews, 2000; Rafiq et al., 2003; Rafiq et al., 2001) developed a Conceptual Building Design (CBD) system using the Structured GA. CBD allows the user to manipulate the system more interactively, a powerful GUI was used which included a number of interactive dialogue boxes for effective user interaction. To allow better interaction with the system at run time, the design hierarchy was made available to the designer. The tree control, as shown in Figure 1, provides basic functionality for manipulating the nodes (different frame systems) and branches in a hierarchy (different design options). Using this facility allows the designer to include or exclude particular design options from the GA search, at the runtime. This facility is considered to be useful in a number of ways. It allows the user to force the GA search to follow a particular branch of the design hierarchy, which may not be considered by the GA as a best choice. This is also useful if the design brief requires a particular construction material to be used or a designer/client prefers a particular floor system, etc. to be considered.

In this limited interaction the system allows the designer to trace the design evolution process during a whole run of a GA operation. This is an important facility which adds transparency to the otherwise ‘black box’ GA operation. For example by clicking the mouse in a point on the graph, the corresponding details of the concept is shown in the second window. This facility was also made available during a genetic experiment while the GA was paused. An example of the use of this facility is presented in Figure 2.

The system also allows pausing the GA search at any time and changing either the GA parameters (e.g. mutation and crossover probabilities, etc.) or directing the search to specific branches of the design hierarchy.

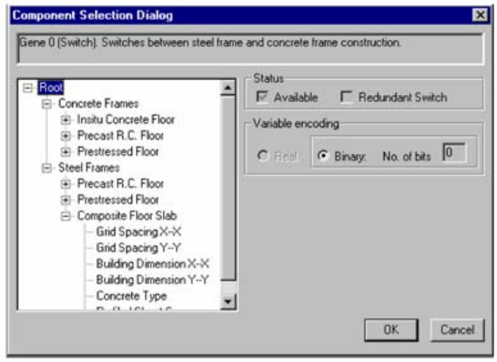

Fig. 1. Dialogue box representing the design hierarchy.

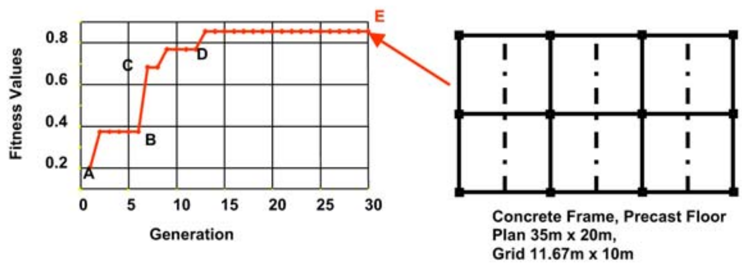

Fig. 2. Tracing design Evolution during a GA run.

Grierson and Khajehpour (2002) used Pareto optimisation techniques for multi-criteria conceptual design, involving genetic-based stochastic search and colour-filtered graphics. In this investigation, a large set of Pareto non-dominated designs were captured. They then used a computer colour filtering of the Pareto-optimal design set and created a large body of informative graphics that identify trade-off relationships between competing objective criteria, as well as design subsets having particular designer-specified attributes. A detailed illustration of the method for the cost-revenue conceptual design of high-rise office buildings, including several examples was presented. The work of Grierson and Khajehpour is an excellent example of knowledge discovery using a simple visualisation tool, and it demonstrates that by using visualisation tools effectively, it possible to discover the interrelationships between design parameters more readily.

Research in Plymouth Engineering Design Centre by Parmee and Bonham (1998) resulted in development of an Interactive Evolutionary Design System (IEDS) based on a system of iterative redefinition of variable and objective space by a designer. These ideas evolved from many years of research in using evolutionary computing to aid engineering design, starting from general ideas to locate and analyse robust regions of the search space. Development of cluster-oriented genetic algorithms (COGAs) allowed inclusion of user preferences between objectives to direct co-evolutionary search (Parmee et al., 2000). COGA extracts regions of good solutions from a GA run by filtering high performance solutions as the search progresses. More recently work on visualisation of COGA data has included the development of a novel technique called parallel coordinate box plots (Abraham and Parmee, 2004; Parmee and Abraham, 2004), that uses the parallel coordinate technique developed by Inselberg and Dimsdale (1994) to visualize many variables at once and compare the distribution of solutions between objectives using statistical analysis and discover overlap between various objectives.

The Interactive Visualisation and Clustering GA (IVCGA)

A major objective of the IVCGA, developed by Packham and colleagues (Packam, 2003; Packham and Denham, 2003; Packham et al., 2004; Rafiq et al., 2004), is to assist the designer through interaction to explore a range of feasible and innovative solution that best fit the design brief requirements. This process of exploration of search and solution spaces is more useful at the conceptual stage of the design process where design information is ill defined.

It is argued that such interaction is fundamental in real life design problems which are multi-dimensional, multi-criteria and multi-disciplinary in nature. Experts from different disciplines can interact individually with the system to explore their own areas of interest and evaluate the effect of changes that they propose on the overall design. It therefore, enhances the awareness of the project team on various aspects of the project which could lead to a mutually acceptable solution. This can lead to discovery of new knowledge about the specific regions of the search and solution spaces and more importantly understanding of collaborative design issues.

To this end, in the IVCGA the focus is on user interaction right from the start, allowing the user to freely interact with specific regions of the search space. Relating to the categories of visualisation and interaction discussed earlier, the IVCGA exhibits a number of unique features:

Firstly, in terms of visualisation the user is able to choose a number of high dimensional visualisation techniques which can help in understanding the relationship between design variables (i.e. 2D and 3D scatterplots, scatterplot matrix and parallel coordinates), additionally the data can be displayed in alternative coordinate systems, (i.e. 'Principal Components', 'Independent Components').

Secondly, a novel clustering technique based on kernel density estimation identifies the clusters in terms of the design variables. Clustering can be performed in alternative coordinate systems such as the principal components that reveal the 'natural' clusters in the data. Colour is used to identify different clusters.

Thirdly, in terms of interaction the user is in full control of the process and is either able to 'zoom in' in specific regions of the search space, i.e. on those regions containing specific colour coded clusters, enabling a more concentrated and focused search 'inside' such regions, or to extend the search 'outside' these regions to explore other possibilities which has not been currently discovered by the GA. It is both these cases which allow human experts to use their domain knowledge to guide the search to those areas of the search space which may meet differing, and possibly changing, design requirements. The nature of the IVCGA interaction places it inside the broader definition of IEC.

The Application of the IVCGA to Conceptual Building Design

Typically building design involves a number of individuals from a variety of disciplines, each with a differing emphasis on the design requirements. Thus, the objective of the study, presented in this section, is to illustrate how the IVCGA can be used in a multi-disciplinary design environment. The exercise has been conducted in close collaboration with an Architect, a Structural Engineer and a Heat and Ventilation Engineer, and it is noted that the differential requirements of each are:

- The Architect – Space, functionality and appearance and user comfort.
- The Structural Engineer – Building stability, strength and safety.
- The Heat and Ventilation Engineer – Mechanical, electrical, heating cooling and ventilation systems.

In this example, only two construction materials, concrete and steel, are included. Choice of suitable construction material could sometimes be a determining factor in selecting design options.

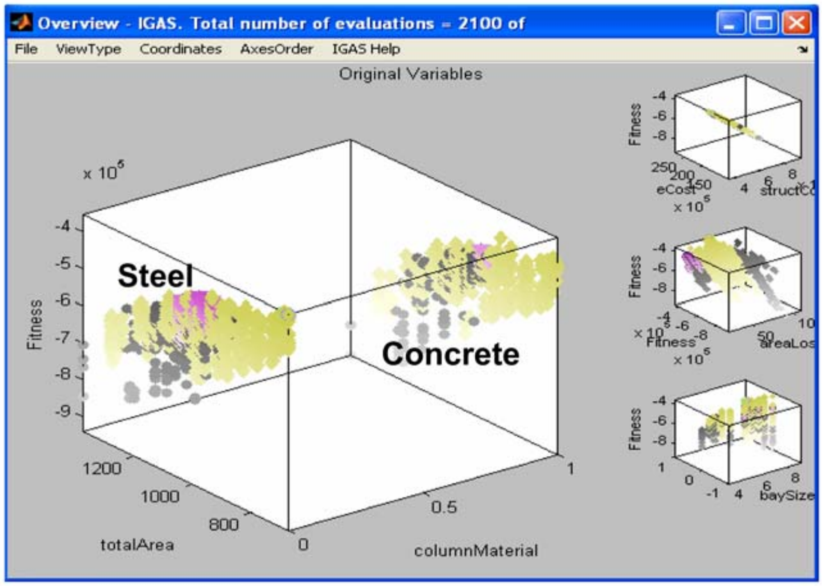

Fig. 3. Visualising solutions in Variable and Objective Spaces.

In Figure 3, concepts generated for each construction material (steel and concrete) is distinctly separated. This is a clear advantage of visualisation tools, which allow designers to investigate each alternative construction material independently and assess the suitability of each alternative against the design/client requirements. In most figures presented in this section the information is presented in the 'objective space' rather than the 'variable space'. This shows another distinct feature of the IVCGA is the ability to present data in either variable space or objective space. At times an objective space representation may be preferred to variable space when design variables are discrete variables.

To satisfy the architectural space requirements for this preliminary study, it is assumed that a major architectural requirement is the amount of available open space: A flexible floor area could be used by various clients with different functionality requirements throughout the life of the building. Therefore, there is a need to minimise the floor area lost due to columns and fire escapes. As the existence of columns in the floor makes the area around the columns restricted for use, it was decided to use a 1 m^2 unusable area for each column. In this study, a typical floor area of 1000 m^2 is assumed.

Figure 4 shows a population of designs generated after the first 20 generations of the GA. The frames on the right hand side show two alternative floor layouts in two different construction materials (steel and concrete). Both layouts satisfy the architectural requirement of minimum area loss. As the requirements suggests, fewer columns and other restrictive structural elements mean more letable floor area and hence more long term revenue.

The user is able to define which variables are plotted against each other, enabling designers to investigate any interrelationships between various design parameters, very quickly. The additional use of colour enables the user to emphasise the clusters that are important to the user whilst keeping other interesting data also available. For example, in Figure 4, concepts presented by cyan and magenta colours represent clusters of high fitness solutions.

Not only does the use of colour identify clusters of good designs, but also enables the designer to view individual solutions in the vicinity of these clusters in order to learn more about the interrelationship between design parameters. A particular strength of the IVCGA, is the ability to zoom in on particular areas of the solution space and to conduct a more focussed search in that area.

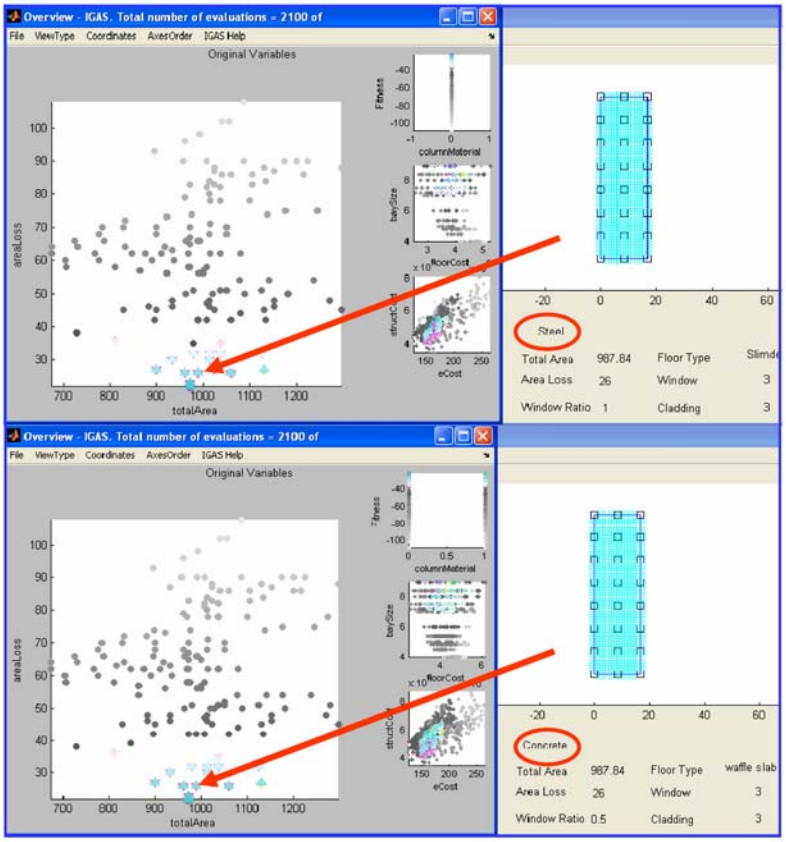

Fig. 4. Alternative concepts in two different construction materials.

To illustrate this, Figure 5 shows a 2D representation of the designs generated by the GA, based on the structural requirements. The left hand frame presents the entire population generated by the GA. No restrictions or filtering of information, to discourage the generation of unfeasible solutions, have been implemented. The rectangle on the left hand frame is interactively drawn by the designer, using the mouse, around the vicinity of 1000 m^2 required floor area, as was specified in the brief. The frame on the right hand side of Figure 5 shows only solutions which are enclosed inside this region. At this stage the system allows the designer to either view current designs generated by the GA within this region or conduct further runs the GA to populate this area with more designs. If this option is selected, the system automatically penalises any designs outside this region if generated by the GA operation. This feature of the system, which interactively and dynamically defines constraints to the problem, is a unique and very useful decision support tool.

A similar investigation could be conducted by each member of the design team to identify regions of suitable designs that best satisfy their individual disciplinary requirements. Finally, these areas are superimposed on each other to identify a mutually inclusive region that partially satisfies the requirements of all disciplines involved in the design. The frame at the left hand of Figure 6 presents all designs generated during separate runs of the GA. The cluster coloured copper represents all design that satisfies energy requirements. The green cluster represents Structural Engineer requirements and the cyan colour cluster represents the preferred region by the Architect. The red circle is the

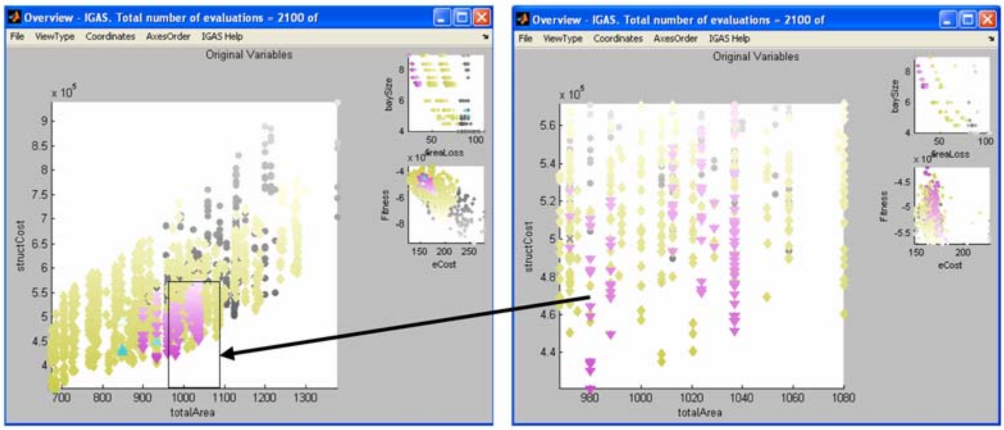

Fig. 5. 2D presentation of the most suitable region for the structural requirement.

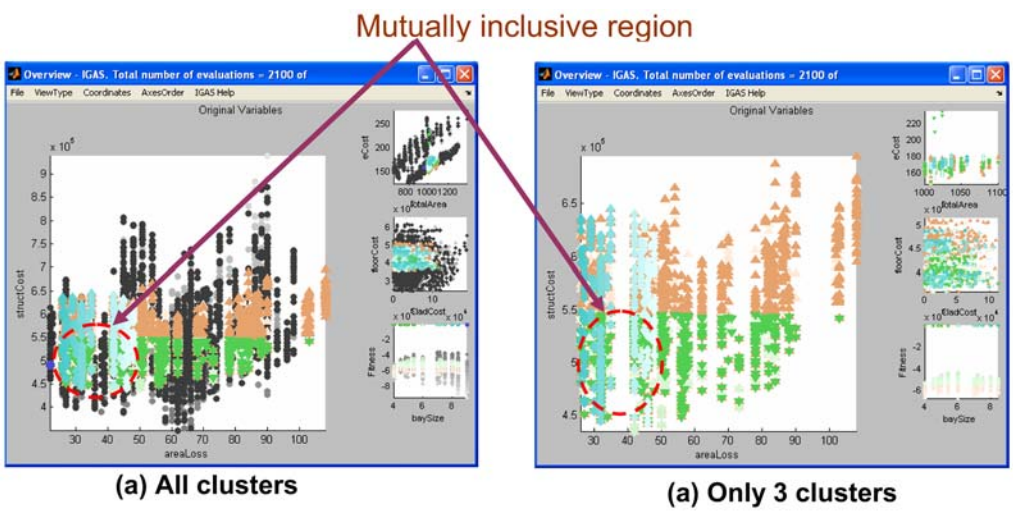

Fig. 6. Mutually inclusive region for all three disciplines.

mutually inclusive region that partially satisfies the requirements of all parties involved. The frame at the right hand side of Figure 6 only shows clusters of suitable designs identified by the three disciplines independently.

Figure 7 present the above information in 2D and 3D scatter plots showing all design alternatives generated during separate runs of the GA. The cluster of designs coloured magenta represents the mutually inclusive region that partially satisfies the requirements of all parties involved.

Conclusions

The use of interactive visualisation undoubtedly gives confidence to the designer particularly at the conceptual stage of the design process by allowing her/him to conduct a human-led search in order to explore many possible solutions that satisfy design/client requirements. The IVCGA, is an effective decision support tool as it presents the designers with the opportunity to conduct search ‘inside’ and ‘outside’ the defined search and solution spaces and to evaluate the merit of each design generated,

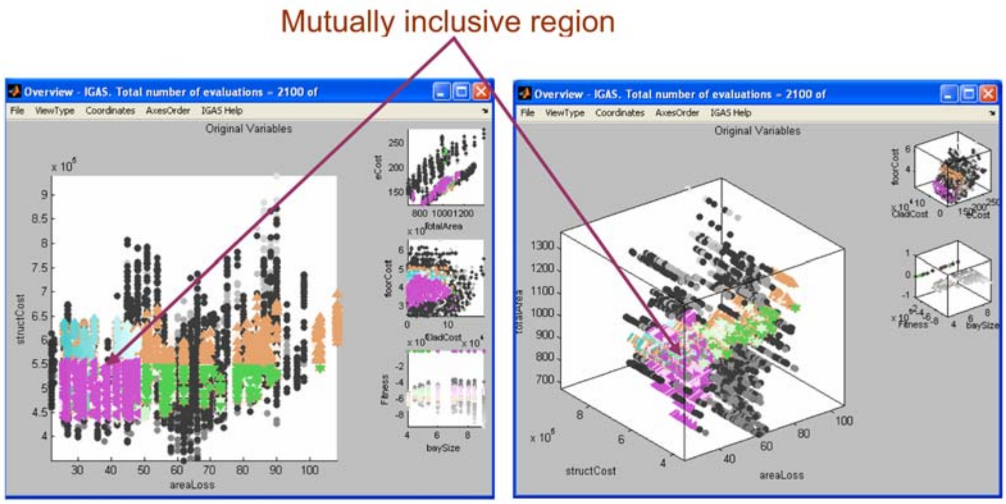

Fig. 7. Mutually inclusive region for all three disciplines in 2d and 3D views.

in term of existing or new design requirements. Visualisation tools, such as the IVCGA, enhances the multi-disciplinary design team members' understanding of the overall design issues and the consequences of the effect of changing one parameter or objectives on the overall design. Using visualisation tools it is possible to identify that region of the solution space that partially satisfies the requirements of all parties involved. Due to the fragmentation of activities between disciplines, agreeing on a compromise design framework presents difficulties in current multi disciplinary design practice. It is hoped that the use of tools such as IVCGA can facilitate better communication between parties involved in the design process.

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