

INTERACTIVE VISUALISATION AS A POWERFUL DECISION SUPPORT TOOL FOR CONCEPTUAL DESIGN

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ABSTRACT

Recent advances in evolutionary computation (EC) have made it possible for researchers to develop decision support tools that to some degree assist designers in decision making. Some of the difficulties with the EC are that they generate a population of alternative solutions to choose from and they are generated in a 'black box' mode, where there is little or no user interaction. The research presented in this paper is using an interactive visualisation tool that allows designers to conduct a human-led exploration of the solution space that has been generated by the EC. Multi-disciplinary design team members can interact independently with the system to explore and identify regions of the solution space which best meet their disciplinary objectives. The visualisation tools also allow them to find a common framework for multi-disciplinary design. This research then post-processes the data inside the region of the agreed framework, using a Pareto algorithm, to isolate non-dominated solutions for selection purposes.

KEYWORDS

Evolutionary computation, Visualisation, Conceptual design, Decision making.

1. INTRODUCTION

Successful application of evolutionary computation (EC), particularly genetic algorithms (GAs) to solve multi-dimensional problems has shown to be promising. Applications of EC in building design goes back to the early 90s when Grierson & Pack (1993) attempted simultaneous sizing, topological and geometrical optimisation problems, not possible with conventional mathematical programming techniques. They approached the combined optimisation problem of planar frames, by first taking a simple example and later extending the approach to a more detailed skeletal structure resembling a building in section. They also applied an approximation technique to analyse the frames generated by the GA in order to significantly reduce the computational effort required. Rajan, (1995) conducted a similar investigation using trusses instead of frames. In addition to member size variation, Rajan studied techniques that simulated the removal of non-essential bracing members from a truss. Jenkins, (1994) reported the need to investigate re-analysis techniques to improve the computational efficiency in structural analysis procedures.

Parmee and Bullock, (1993) described how the GA has been successfully applied to the design of a hydropower scheme, which incorporated the optimal geometric design of a concrete arch dam to resist self-weight and hydrostatic forces. In their work, they recognized that radically different geometric forms (i.e. different curvatures) embodied different design concepts that warranted consideration. Subsequently they proposed that an optimisation based on the Structured Genetic Algorithm (SGA), developed by Dasgupta and McGregor, (1991) was appropriate for handling multiple different concepts simultaneously.

From 1997 to the present day, there has been noticeable growth in interest in the application of GAs specifically to conceptual building design. One reason for this is that building design problems are highly multi-dimensional, multi-criteria and multi disciplinary problems with lots of inherently conflicting criteria. Studies by Grierson and his co-researchers in Waterloo, (Grierson and Khajehpour, 1999, Grierson and Park, 1997), Rafiq et al. in Plymouth (Mathews et al., 1996, Rafiq and Mathews, 1998, Rafiq et al., 2003) and Miles et al. in Cardiff (Miles et al., 1995, Miles et al., 2001, Sisk et al., 2003) are perhaps the first people who have made particular contribution to this area.

2. MAJOR ATTRIBUTES OF AN INTERACTIVE VISUALISATION SYSTEM

Interactive evolutionary systems can be categorized into two broad groupings: Where the user makes a subjective evaluation at the selection stage, and where the user changes design objective preferences (see also Parmee, 2002, for similar categorisation.)

In terms of visualisation two broad approaches can be identified. Firstly, it is the result of the search process which is presented to the designer, thus in the single objective case the classic approach has been a simple fitness plot and in the multi-objective case, plotting the Pareto front or Pareto surface (the work of Grierson and Khajehpour, 2002, puts this technique to good effect). Secondly, in more sophisticated systems the focus has been on the visualisation of the GA search process itself: This may involve tracing the ancestry of the evolving individuals or representing the genetic composition of individuals (see Hart and Ross, 2001, Collins, 2002, and Smith et al., 2002). In all cases 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.

A major objective of an interactive visualisation system, presented in this paper, is to assist the designer through a human-led interaction to explore a range of feasible and innovative solutions that best fit the design brief requirements.

The 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. The interactive visualisation process is fundamentally different from the traditional search and optimisation as it opens a human window in which the user freely interacts with the system to explore and visualise the search and solution spaces to find regions of more promising solutions that suit the design requirements. It does not solely rely on encoded quantifiable objectives as the search is guided by the human-led interaction and new boundaries, constraints and requirements are dynamically introduced. Many conceptual design considerations that are qualitative parameters can be incorporated through direct human-interaction. It is capable of visualising multi-dimensional problems and presenting information interrelationships between design parameters and/or objectives.

3. AN INTERACTIVE VISUALISATION AND CLUSTERING GENETIC ALGORITHM SYSTEM

The Interactive Visualisation and Clustering Genetic Algorithm System (IVCGA) developed by Packham et al. (Packham, 2003, Packham et al., 2004a, Packham et al., 2004b, Rafiq et al., 2005) is a system that was designed and built to focus on user interaction at the outset and allows the user to freely interact with specific regions of the search space. The work is centred on a user interface that allows the user to 'zoom in' to specific regions of the search and solution space, defined by the user, and create new data using further GA runs.

By including a flexible interactive user interface supported by visualisation tools, the IVCGA allows the designer to conduct a focused and concentrated search inside regions of high performance solutions or to extend the search outside the boundaries of the current search. It is possible to incorporate non-encoded design requirements into the human-driven search and evaluation process.

In the IVCGA, the constraints are removed as much as possible and *all* the data produced by a short number of the GA runs is initially available for visualisation. The user can then choose to keep or filter out information as required interactively. The data is then clustered using a fast, novel technique according to user requirements, based on parameters of objectives spaces. The advantage of this method is that data is generated very quickly and low performing, but potentially interesting solutions are not filtered out from the results by imposing constraints.

The authors believe that by combining flexible user interaction and visualization capabilities with the power of the evolutionary computation in a human-driven interactive system, such a system could deliver invaluable decision support and knowledge discovery, as advocated by Parmee et al. (2000) and Mathews et al. (1995).

The IVCGA was designed to offer the following features:

- The fast generation of diverse data by running a simple GA for a low number of generations to reduce the number of function calls with normal crossover and mutation rates. The diversity of solutions is maintained by applying a high mutation rate when duplicate solutions are identified.
- An easy to use interface that allows direct manipulation of the data and views. Various high dimensional visualization techniques are supplied to enable understanding of the data from different viewpoints and a combination of parameters.
- An automatic clustering procedure is built into the system that identifies clusters relevant to the problem in hand. Colour is used to highlight important clusters, enhancing perceptual understanding of the data.
- Extensive interaction is supported allowing the generation of further data with the GA inside or outside regions identified by the user or clustering algorithm. The definition of clusters can be modified by the user or even created manually, ensuring complete freedom of search and human-led exploration of the search space.

The objective of this study is to post-process a large amount of data within a region of the solution space that has been agreed by the multi-disciplinary design team as the mutually inclusive region, to present a smaller set of non-dominated solutions using Pareto optimal techniques for further consideration by the multi disciplinary team.

4. PROBLEM DEFINITION

In this study three disciplines: the architectural; the structural engineering and the health and ventilation engineering disciplines are included. Two construction materials (steel and concrete) are used in the case studies.

Although solutions generated by the evolutionary computation (EC) use a complex objective fitness evaluation process, considering essential design requirements related to each discipline, mostly the optimum layouts of the buildings are presented as a visual measure of fitness evaluation for presentation purposes. At the end some examples of the interface between the visualization tools and 3D CAD systems are demonstrate, but work in this area is in its infancy.

To simplify the problem, 9 independent parameters (construction material, number of floors, bay size, number of bays in x-direction, cladding type, floor type, window type, window ratio and unit land cost) and 5 dependent design parameters (total area, bay size, number of bays in y-direction, building length and width) are used.

Independent parameters are the GA variables, values of which are assigned through the GA optimization process. Values of the depending parameters are determined from the independent GA variables. Four objectives are defined by the multi-disciplinary team (area loss, energy cost, floor cost and structure cost). These objectives are related to the three disciplines involved in a multi-disciplinary design.

Multidisciplinary issues regarding the design of a commercial building with a total lettable area of 8000 m² are investigated. Maximum number of storeys is limited to 8.

There are over 8 million possible solutions using EC. Using the IVCGA the total number of solutions initially generated was 6300 alternative solutions. The mutually inclusive region consisted of 1857 individual solutions. Number of non-dominated solutions isolated by the Pareto technique was 164. Out of which 112

solutions were steel structures and the rest were concrete structures. For details of multi-disciplinary exploration and identifying regions of mutually inclusive designs, refer to (Rafiq et al. 2008a, Rafiq et al. 2008b).

5. EXPLORATION OF SOLUTION SPACE USING IVCGA

An advantage of the IVCGA as a powerful visualization tool is that it allows interactive user interaction to efficiently explore the solution space. IVCGA consists of two main modules: the GA as a powerful search engine and the visualization tools as an aid for interactive exploration.

During the GA search process no constraints are permitted. The GA runs for 21 generations and with a standard population size of 100, produces a possible 2100 alternative solutions. This process is repeated for each objective independently.

The interactive exploration process used in this study is conducted in three levels:

1. Independent exploration of the solution space by individual members of the multi-disciplinary team to explore the solution space in order to locate regions which better satisfy their individual design requirements. In this process designers from each of the disciplines run the GA search tool using their own objectives as a measure of fitness for assessing the suitability of individual solutions.
2. Integrated exploration by all members of the design team collectively to negotiate boundaries of the mutually inclusive region of the solution space that partially satisfy requirements of all parties involved. In this process regions selected during the independent exploration are superimposed to agree on the boundaries of the mutually inclusive region. This mutually inclusive region is considered as an agreed framework for further multi-disciplinary activities.
3. Pareto solutions to narrow down and focus the exploration to about 10% of the non-dominated solutions within the mutually inclusive region.

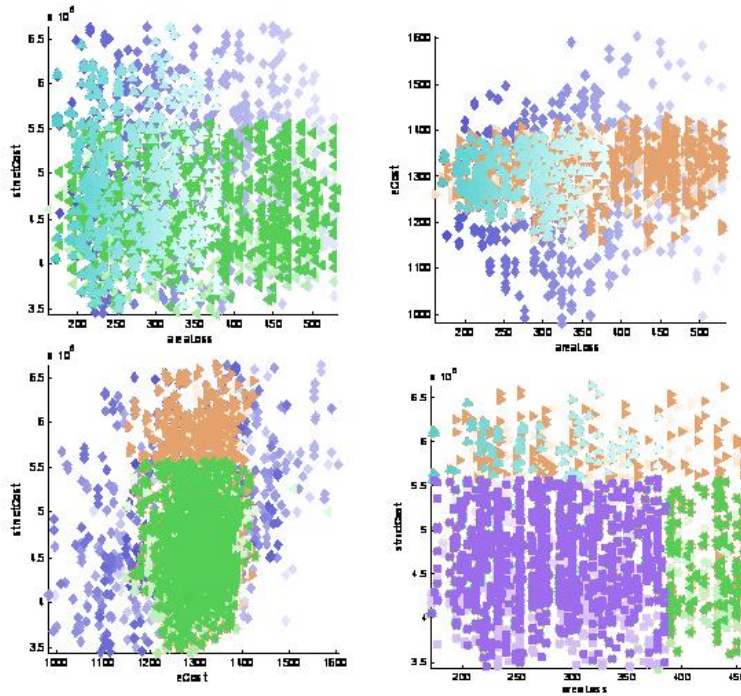
Details of the first two processes can be found in Rafiq and Beck (2008a, 2008b). Here we only focus on the third step which concentrates on pre-processing the data generated by the first two processes to identify a set of non-dominated solutions and explore the suitability of these solutions against the requirements of each the three parties involved in the design.

6. POST PROCESSING OF DATA INSIDE MUTUALLY INCLUSIVE REGION USING PARETO RANKING

6.1. MULTI-DISCIPLINARY EXPLORATION

Figure 1 shows the process of defining the mutually inclusive region of the solution. The top left frame shows superimposing the architectural preferred region of the solutions space, indicated by the cluster of cyan triangles (each triangle represent an individual solution) with the structural engineering region, indicated by the green cluster.

Similarly the top right and bottom left frames respectively represent superimposing process for the architecture and M&E and the M&E and the structural engineering preferred regions. Finally the bottom right frame shows the common area for all three disciplines, the mutually inclusive region of the solution space, signified by the purple cluster.



Cayn = areaLoss, Green = structCost Copper = eCost & Purple mutually inclusive region
Figure 1. Defining mutually inclusive region

A 3-dimensional view of the mutually inclusive region along with a floor plan and some details of two near optimal solutions are shown in Fig. 2.

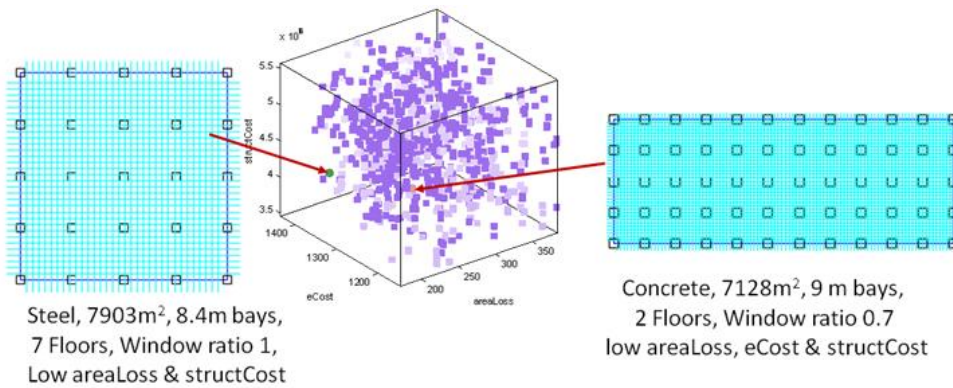


Figure 2 A 3-D representation of the mutually inclusive region along with two candidate designs solutions (one concrete and one steel option)

6.2. POST PROCESSING DATA USING PARETO NON-DOMINATED RULES

Once the mutually inclusive region of the solution process has been agreed by the three disciplines and the framework of the future multi-disciplinary activities are agreed, members of the design team can focus only on solutions within the boundaries of this region (the purple cluster in Figs. 1&2).

As mentioned before, 1857 individual solutions are enclosed within the purple cluster, which by itself is a large solution space to deal with.

In order to narrow down the exploration space, a Pareto algorithm was used to rank solutions within the purple cluster into several Pareto sets based on the non-dominated rule defined by Pareto. This non-dominated rule states that *it is not possible to improve any of the criteria without a compromise, which would worsen at least one other criterion.*

Design solutions within the mutually inclusive regions were divided into a number of Pareto sets as follows:

1. The Pareto algorithm was run using all 1857 individual designs within the mutually inclusive region for three objectives (minimizing areaLoss, eCost and structCost). Implementing this process all non-dominated solutions within the mutually inclusive region were ranked to identify the first Pareto set. There were 64 solutions within this region.
2. In the next step all 64 solutions identified as the first Pareto set were removed and the Pareto algorithm was run with the remainder of solutions and the second Pareto set was identified.
3. This process was repeated until all solutions within the mutually inclusive region were exhausted.

Although 64 solutions in the first Pareto set is plenty to work with, due to the multi-dimensionality of the problem it was decided to combine the two top Pareto sets in the selection process. Fig. 2 shows position of the two Pareto sets within the solution space.

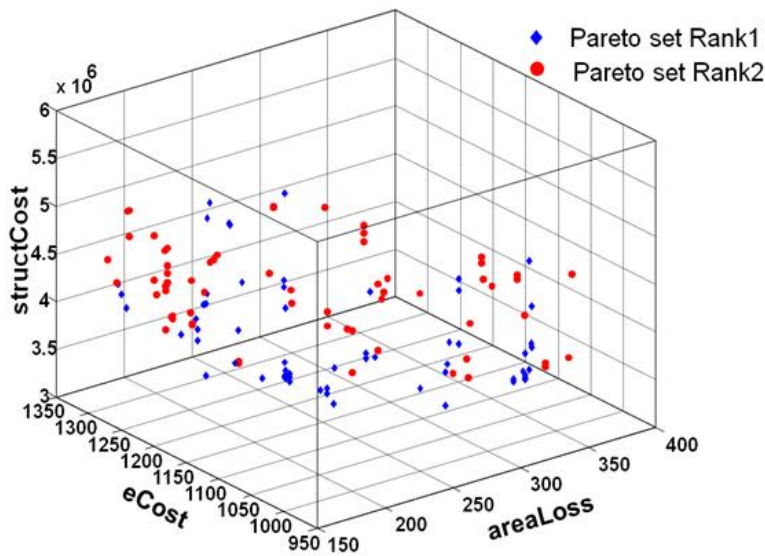


Figure 3 Position of two top Pareto sets

Identifying sets of Pareto non-dominated solutions is useful for the multi-disciplinary negotiation process. It facilitates the multi-disciplinary design team members with the opportunity to:

- Explore the interrelationship between various design parameters and objectives.
- Discover the impact of individual decisions on the decisions of other members of the team and on the overall design and hence the overall cost of the project.
- Discover a deeper knowledge of the overall design issues and knowledge of the boundaries and limitations of her/his own decisions and those of other members of the design team.

- Better appreciation and understanding of the overall design requirements and constraints, which makes it easy to compromise as the whole picture is clearer and there is little room for pushing selfish requirements as is the case in the conventional negotiation process.

Some of the benefits of using the Pareto non-dominated solutions are discussed in the following section.

Fig. 4 shows 2D plots of one objective against another. It should be noted that each plot in Fig. 4 is a 2 dimension representation of a 3 dimension object in Fig. 3. Even in a 2 dimension plot there is a clear Pareto front marked by a red line in each plot, which could be considered as the Pareto front for the two objectives that each plot represent.

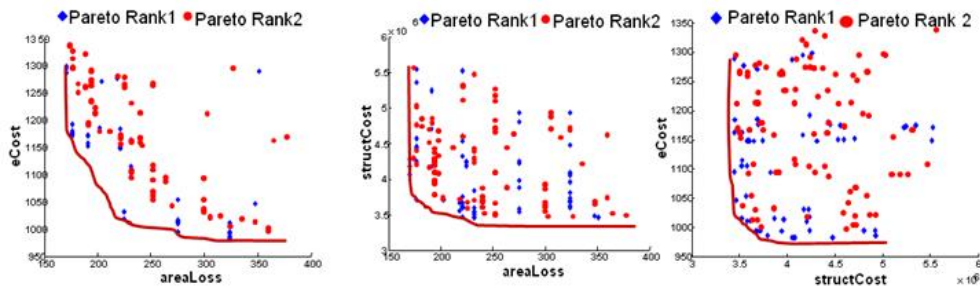


Figure 4 2D Plots of Objectives Related to each Discipline

Information presented in Fig. 4 was transferred into the IVCGA for further exploration. Fig. 5 shows samples of non-dominated solutions for lower areaLoss and/or lower energy cost.

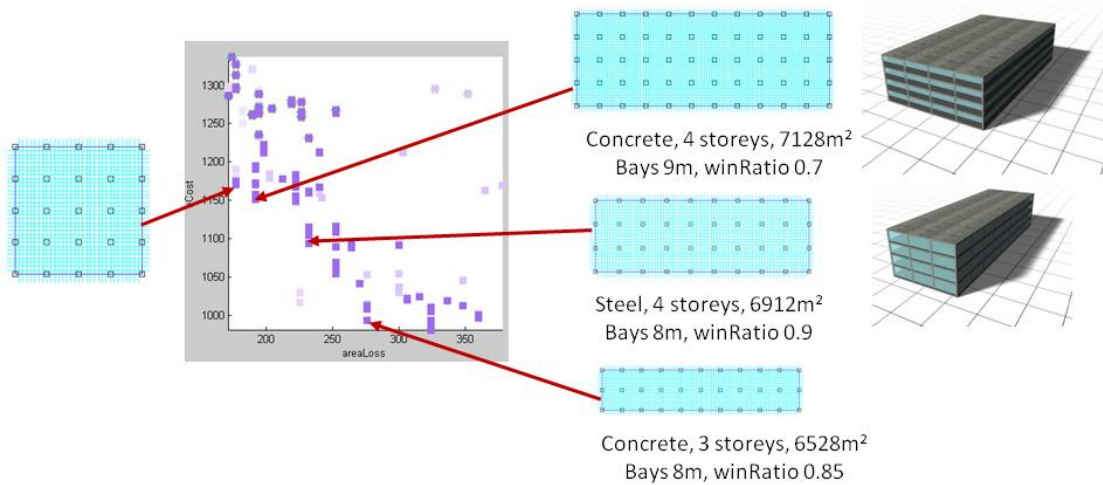


Figure 5 Pareto Designs (Building Footprints) Satisfying areaLoss and eCost Objectives

Designs adjacent to the vertical axis are those designs which have low areaLoss, but their suitability for energy usage is not optimal. Conversely designs adjacent to the horizontal axis which have low energy consumption may not fit in terms of areaLoss. Another interesting finding of the information presented in Fig. 5 is that the total letable floor areas for all designs along this Pareto front are below the required 8000m². This may be an indication that there are no good solutions in the region of 8000m² that simultaneously satisfy both optimum energy and optimum areaLoss requirements.

Figure 6 shows samples of non-dominated solutions for lower areaLoss and/or lower structural cost.

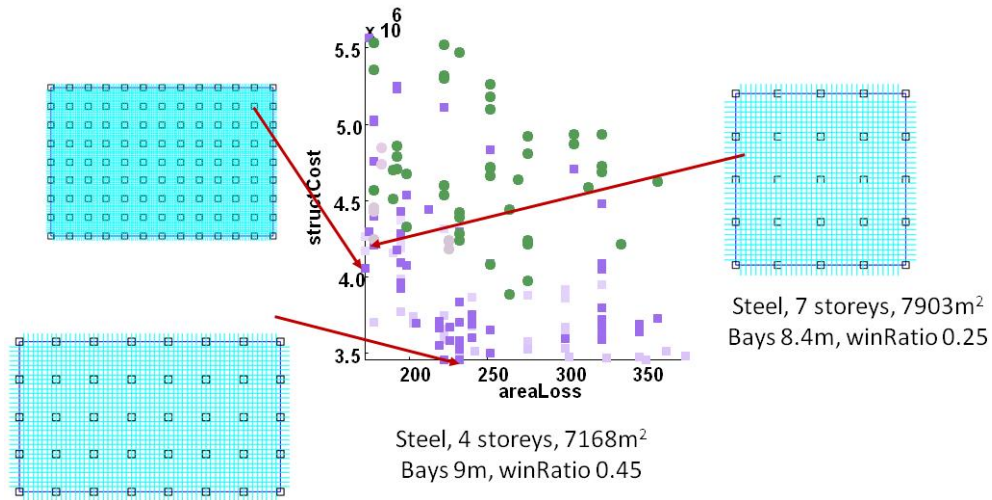


Figure 6 Pareto Designs (Building Footprints) Satisfying areaLoss and structCost Objectives

From Fig. 6 it is clear that good solutions for low areaLoss and moderate structCost having total letable areas close to the required 8000m^2 are achievable. Solutions with lower structural costs are either less than 8000m^2 or expensive in terms of areaLoss, which may not be desirable for the architectural requirements. In Fig. 6 designs belonging to concrete construction material are coloured in green.

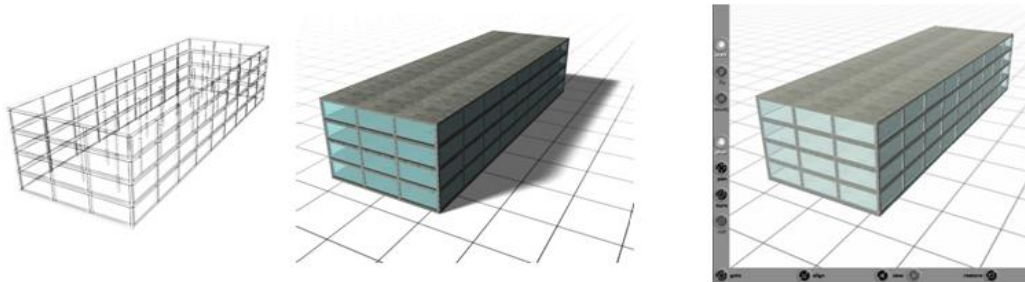


Figure 7 3D CAD model of the steel structured, 6912m^2 , 8m bay, 0.9 window proportion 4 storey building, with the VRML model shown on the right.

Further investigation of figure 7 revealed that most solutions satisfying both areaLoss and structCost belonged to steel frames. It was also discovered that there were no designs in concrete material that satisfy total area requirement of 8000m^2 .

IVCGA facilitates the opportunities for designers to conduct a more focused search for each construction material or any other aspect of the design that enables them to pinpoint desirable solutions within a short time.

7. LINKS WITH CAD TOOLS

Although building footprint is a quick, easy and convenient way for assessing the suitability of designs, it cannot present sufficient details to justify making decisions in selecting final design solutions on its own. Three and 4D technologies are ready for use in design, construction and manufacturing areas. It may be timely to implement these technologies at the conceptual stage of the design process.

We have started preliminary trials in presenting solutions generated by the IVCGA and narrowed down using Pareto optimal techniques using 3D representation and a walkthrough inside and outside of the buildings.

It must be mentioned that although use of 3D representation and a walkthrough inside and outside of the buildings are excellent tools at the final selection stage, where only a few candidate designs are shortlisted for final selection, they are time consuming processes and use of building footprint for preliminary assessment has its own merits. This is one reason which makes integration with CAD tools at the outset of the exploration process unworkable and unnecessary. Therefore interface with CAD system at the later stage is encouraged.

Every 3D CAD system provides tools for the operator to visually assess the model in a real time interactive manner, whether that be by using specific walk through and fly through facilities or the standard panning, zooming, rotating type operations. Access to this visualisation functionality either requires an installation of the full CAD application or a compatible viewer. Certain neutral 3D model formats, such as VRML, provide means of viewing the model without the need for this specialist software. VRML also provides intuitive interactive functionality, enabling the user to easily navigate and view the model. VRML files are text based and are relatively straight forward to automatically generate. For this reason VRML has been selected to further explore suitability of solutions generated by the IVCGA to give the designer a better understanding of these alternative designs.

By interfacing IVCGA with VRML, each design selected from the solution set will be automatically be written as a VRML97 formatted file, processed and presented, giving the user an interactive first person experience of walking around the building.

8. CONCLUSIONS

This paper has demonstrated that IVCGA, as a powerful decision support tool, facilitates user interaction, which allows members of the multi-disciplinary design team to conduct independent exploration of the solution space in order to locate regions which better satisfy their individual design requirements. It also allows integrated exploration by all members of the design team collectively to negotiate boundaries of the mutually inclusive region of the solution space that partially satisfy requirements of all parties involved. In this process regions selected during the independent exploration are superimposed to agree on the boundaries of the mutually inclusive region. This region will constitute a framework for all future multi-disciplinary design activities. The research introduced a novel way of using a Pareto algorithm to narrow down and focus the exploration to about 10% of the non-dominated solutions within the mutually inclusive region. This would assist members of the multi-disciplinary design team to decide on a few negotiated solutions that best suit the multi-disciplinary design/client requirements.

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