# A Future Vision for a Virtual Reality and Search-Based Outline Design Environment for the AEC Industry

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**Abstract**

It is generally accepted that the early stages of design are vital in that they are where the bulk of the costs are determined and also the form of what is to be built is decided. As yet, the early stages of design are not supported by any commercially available software tools. This is in part because the techniques developed by the research community are not sufficiently comprehensive in terms of their functionality. In this paper, a new approach to design for the construction industry is proposed. The approach suggests using an evolutionary algorithm to produce one or more preliminary 3D models which can then be refined, communicated and reviewed using virtual reality rather than CAD which is too formal for early design. The paper outlines a future vision for a VR-search based design environment for outline design processes. It is postulated that the proposed environment will be support a more economical and intuitive way of working than current processes. The resulting environment should also provide a communication tool for the various stakeholders.

## 1. INTRODUCTION

The Architecture, Engineering & Construction (AEC) industry designs and builds bespoke products whose size is such that there is no possibility of building and testing prototypes. Also the products are notable for their complexity. A hospital can contain as many as 8000 rooms, so the number of components vastly exceeds what is found in, for example, a car. So, AEC designers and builders face far greater difficulties than most other sectors. Also, it is often the case that the finished products in most of construction projects do not meet the requirements of the stakeholders (especially the client) in terms of, at least, some of the following: cost, value, design quality, usability and environmental impact. Several studies and research projects in the UK and elsewhere in the world have been put forward to identify the causes and solutions for these issues. The authors believe that there is a huge gap in the provision of suitable tools to help the stakeholders in the initiation and early design stages and that this omission is at least partially the cause of the problems.

The early stages of AEC design, which can have a profound impact on the way in which a project is detailed, contracted, constructed and delivered, are largely untouched by technological progress. Conceptual design is still reliant on human reasoning, although the research community has created some prototype demonstrator software tools to assist the designer. Some of these are for distributed design teams (e.g. Soibelman & Pena-Mora (2000) and Miles et al (2004)) but there are also multi disciplinary tools based on a single work station (e.g. Tizani et al (2005)). Tizani's work has many useful features such as the linking of product and process models, a generate-and-test facility and visualisation tools. However, like many conceptual design tools, it does not have a search mechanism. Khajehpour & Grierson (1999) show that the number of possible solutions for a medium sized building is huge (of the order of 4 billion, Grierson (per comm.)), so without some form of search engine, the designer has very little chance of finding a good solution. Also, design is a knowledge driven process and industry will benefit greatly if the knowledge is captured and represented in a form that allows parts of the product model creation and search to be semi-automated. Outline design research conducted at Teesside revealed that there is tremendous benefit in applying an integrated VR and intelligent system to Reinforced Concrete Building design, (Khatab, et al 2005).

Research using Evolutionary Computation (EC) has developed prototype tools to support search during AEC industry conceptual design (Khajehpour & Grierson, 1999; Rafiq et al, 1999). Cardiff University is one of the leading centres for this work (e.g. Miles et al, 1999; Sisk et al, 2003) with a special emphasis on strong industrial collaboration to ensure the relevance of the techniques. A limitation of the above EC tools is the spatial reasoning. They can only cope with buildings with rectangular floor plans. Recent work at Cardiff shows how to overcome these deficiencies and provide methods which can handle more complex shapes (Shaw et al., 2005). Another major problem is the need to deal with the multi-disciplinary nature of the AEC industry. Much work has been done on structural search but there has been less emphasis on how to incorporate the needs of architects, building services engineers, construction methods, etc. Some software systems contain routines to deal with proximity relationships and spatial planning for single floors (e.g. Fernando et al, 2001) but these assume the available space is large enough to allow any option which is generated. Sisk et al (2003), Rafiq et al (1999) and Khajehpour & Grierson (1999) have developed systems which take a limited account of architectural and building services requirements. Therefore, the current systems have demonstrated the feasibility of using EC for aspects of AEC conceptual design, but further substantial fundamental research is needed before the techniques can deal with the full complexity of the domain.

The later stages of the design process are well supported by analytical software, e.g. FE analysis and CAD. In recent years, designers have started moving to 3D CAD models and more recently to parametric 3D (e.g. Autodesk Revit). However, 3D CAD can be time consuming and so there is a reluctance to use it, especially during the earlier stages of design. Additionally parametric models can be computationally demanding and therefore cumbersome (Sacks et al, 2004). They are also difficult to implement in early design where the design is still fluid and lacking in details, and significant topological changes may yet occur. There are some research prototypes that will generate 3D models automatically (e.g. Tizani et al, 2005), but their 3D visualisation does not allow interactive editing and amendment by the user. Despite the cost of producing 3D models, they are very useful to the designer, for example, in detecting clashes. Such models can be linked to animation routines and Virtual Reality (VR) software to provide walk-throughs, construction simulations etc. (Op den Bosch & Baker, 1995) although VR sourced from CAD models tends to be excessively large because of the complexity and detail inherent in CAD (Whyte et al, 2000). Recent research projects conducted at Teesside University revealed the possibilities of producing a design solution for RC frames from limited information, at the outline design stage, utilising simple knowledge rules and visualisation technologies (Khatab et al, 2005). Also, designers can view the VR model from initial information in the database of the RC Frame using a desktop computer prior to any CAD development.

A linked GA search and VR modelling design environment was developed by Kim & Cho (2000). Also, Liu et al (2004) describe a system to design table lamps. Both application domains are simple and the VR is used to visualise the output from the GA. There has been work to use VR as a design as opposed to visualisation tool. For example Ford (2005) uses VR coupled to haptic feedback to test new designs. However, most users of VR employ it as a means of checking, rather than allowing interaction with the design. A notable exception is the work of Liu et al (2004) who use haptic interaction to modify designs to produce the sort of complex, curved shapes that occur in domains like automotive design.

One of the main conclusions of 'VR RoadMap: Vision for 2030' workshop which was organised by the authors and held in Manchester, in Jan 2006, was the identification of the need for an AEC design environment in which EC (Evolutionary Computing) and VR can be coupled to create an innovative conceptual design, this being the subject of this paper. The main conclusion from the above discussion is that to date, nobody has linked EC search and VR modelling to produce a complete outline design environment. In this context, the objective of this paper is to outline the specification and a framework for a future vision for VR/Search-based outline design environment.

The following sections discuss the development of a framework for integrating EC and VR to innovative outline design process and methodologies to deliver tools and methods.

## 2. INTEGRATION OF EVOLUTIONARY COMPUTING (EC) AND VR FRAMEWORK

The coupling of EC and VR together with other software tools should enable the creation of an AEC industry design environment in which the initial conceptual design is created using EC tools which are then passed to an immersive VR so that stakeholders can review and communicate an outline design. The EC component would produce basic 3D models which represent good solutions in terms of the myriad of possibilities which are available. These 3D models could then be used as a starting for the designers to initially, critically review and amend and develop interactively. The VR module would allow further details to be added, so that the output from the process would be an outline design of a standard which could be passed to a CAD package to be developed into a fully detailed design. The objective of this paper is to present the framework for integrating EC and VR and to elaborate on the development needed to achieve the overall aims described in this paper. An architecture of the proposed design environment is shown in Fig. 1.

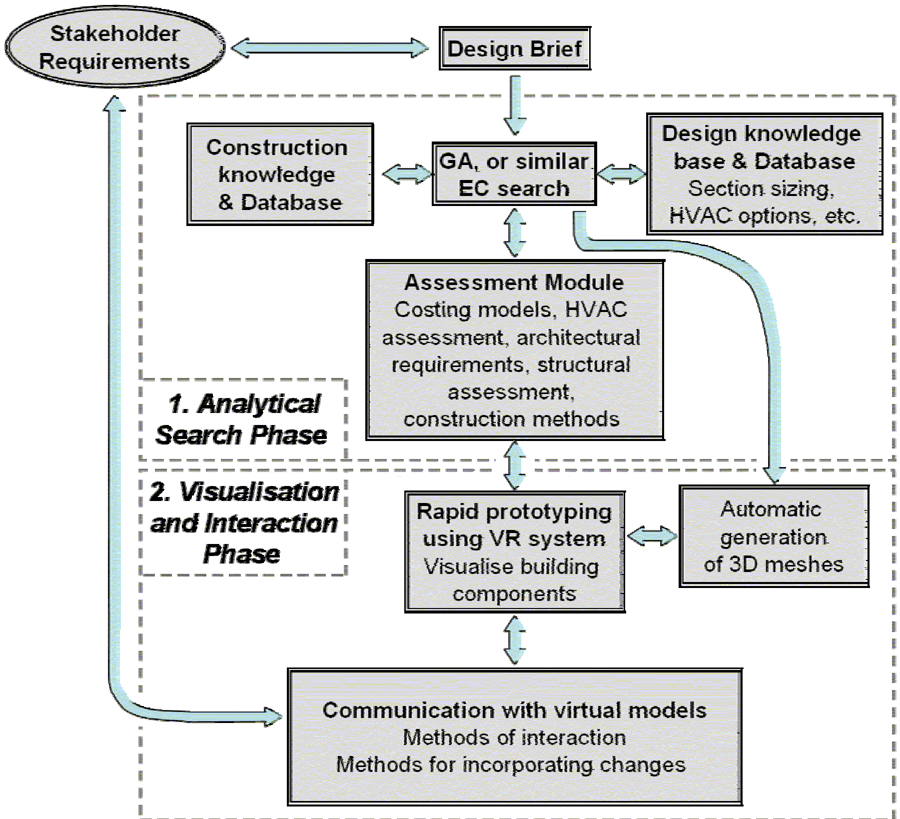


**Fig.1 Framework for integrating EC and VR at the outline design process**

The framework is composed of two main interrelated phases: analytical search and visual interaction. These interact in real-time with the design brief and stakeholder requirement processes.

There is an established body of work on handling stakeholder requirements and the client brief electronically as used, for example in the INTEGRA project (Miles et al, 2004) which built upon the work of Rezgui at al (2003). In the proposed system, all the design constraints would be within the Design Brief module and would be expressed in either numerical or natural language forms, with the latter being converted into fuzzy rules possibly using Fodor & Roubens' (1994) work as further developed by Parmee (2001). After translation the constraints will be passed to the assessment module. It is anticipated that the brief will also have to contain information such as the intended cladding, space requirements, preferred heating / ventilation strategies, ground conditions, etc.

In the analytical and search phase, it is intended that the EC module would use the representation of Shaw et al (2005) for the structure. It is anticipated that the architectural and building services representation will mainly use a generative geometry such as suggested by Leyton (2002). This is a new and untested approach but it potentially offers significant flexibility. The complexity of the linked architectural, structural, foundation and building services design requirements poses a significant challenge which is more complex than has been handled in any work undertaken to date. However for the proposed environment to succeed, it is vital to achieve a fully coupled search.

The Assessment Module (AM) within the analytical and search phase will act as the EC fitness function and also provide information to help designers judge the impact of their amendments when using the VR components. The AM, in addition to analysis software for the structure etc, requires a cost model.

It will not be possible to use a single cost model (e.g. Miles et al (2004)) because the complexity of the design will increase as further detail is added. Hence a new form of dynamic cost model will have to be developed. The AM will require a process model to assess constructability issues both for the EC and VR. Communicating the EC search results to the designers will need advanced techniques because of its extreme complexity. The only suitable method is the work of Parmee & Abraham (2004).

The design knowledge base and database will largely contain standard data relating to available components such as structural steel sizes, doors, etc. These will be available in a variety of formats including graphical representations which could be dragged and dropped into a VR simulation.

With the visualisation and interaction phase, for the Rapid Prototyping VR (RPVR) module and its linked communication module, a powerful and advanced visualisation tool such as the Powerwall VR system (Fakespace, 2005) is needed to provide the basic user interface. Powerwall provides advanced features such as gesture recognition to activate commands, head tracking to facilitate the correct perspective of stereo images as the user's view changes, hand tracking to enable direct interaction with the visualised objects and holographic quality representation. In the proposed system it is suggested that such visualisation facilities need to be considerably enhanced with additional user interaction and communication functionality to produce an advanced design facility which will take the EC's basic 3D models and allow the designers to evaluate, change and add detail.

In the design evaluation stage, the designers will choose a few of the EC's more promising 3D models as a basis for further development using the RPVR system. Using VR rather than CAD introduces challenges. For example, it will be possible to move structural members to locations where they are unconnected with the rest of the structure because the VR model will not be parametric. Such moves (with appropriate warnings) should be allowed because the designer may then make other alterations to restore continuity. The RPVR needs to be linked to the AM, to provide instant feedback on the implication of changes in terms of cost, performance and constructability. As much as possible should be managed directly through the visualisation. Determining exactly what the different stakeholders need to see and how best to present it to them will be important in the development of the environment. This can only be achieved by experimentation with real designers to assess their needs.

The 3D model generated by the EC will lack the features required for some stakeholders, for example finishes and drainage. For clients, finishes will be an important feature as they will want to see the design as it will appear after construction and drainage is too complex in terms of topological reasoning to be undertaken in conjunction with the rest of the EC design. To deal with these different aspects, it will be necessary to have facilities to use the VR system as a design tool and also in different modes so that it can understand what the designer is trying to achieve and which parts of the AM software should be activated.

There will therefore have to be facilities within the VR System for adding new objects to the model and giving them appropriate properties. VR technology doesn't offer such features and so this is a research need. As designers amend and add to the VR model there is the possibility of constraint violations occurring. The AM will have be used to check for these so it will somehow need to be provided with intelligence to enable it to track what the user is doing and understand and comment on design changes. How to achieve this is another challenge as is the linking to an appropriate form of the cost model as the amount of detail in the design increases.

## 3. FUTURE ACTIVITIES

In order to deliver the processes and modules identified above, development and research activities have been established. These can be grouped into the following:-

1. Detailed design of system architecture: This involves drafting the specification for the system architecture in Fig. 1. Detailed functionality and processes of each module are being developed and documented.

2. Knowledge elicitation and encapsulation: Knowledge about outline design which includes the development of relationships between components sizes and factors like weight, spans, floor height, etc. Knowledge elicitation will also include construction methods for example what type of foundation that might suitable for a particular building, the piling equipment that can be used under different spatial and environmental constraints. Also, the type of cladding system and components can be considered at the outline design stage. The research team will engage industry design and construction experts in the knowledge elicitation process.

3. GA and Assessment Module: This includes initial EC search creation including selection of the algorithm to be used and development of representation and constraint handling for the evolutionary search engine.

4. Development of a VR rapid prototyping system which will be able to visualise initial solution that will be developed from the above two activities. This also includes the generation of 3D models from the EC search engine. User interactions and communications with VR models will be developed to provide the means of editing and adding details to the design plus handling user feedback.

5. Experimentation. This will be an ongoing process as the processes and software are improved. Industrial case studies will be used to test and validate the model based on the methods used in the VIRCON project (Dawood et al, 2005). It will also involve the use of people from industry who have not previously seen the software to experiment with tools.

## 4. TECHNOLOGICAL ADVANCES

Significant technological advances are required before the framework outlined in fig. 1 can be realised and it is vital that the result is an intuitive and interactive, designer friendly process where the designers are in control at all times. VR has been chosen in preference to CAD for the graphical representation because VR is less computationally demanding (Whyte et al, 2000) thus facilitating interaction with less computational overhead than CAD (Sacks et al, 2004). Also CAD requires a level of detail and complexity which is not available in early design processes. It is recognised that there can be a risk attached to this decision but efficient software that will run quickly is important because the 3D model will be linked to other design software (e.g. structural simulations & constraint checking). Speed will permit instant feedback to on-line changes. For example, the removal of columns will alter beam depths and so the building height will change and hence the cost. Although some of these features are available in parametric CAD, it cannot cope with such significant topological changes (Sacks et al, 2004).

Solutions to these challenges will be devised in this project in collaboration with practising designers and a leading design software company. The involvement of the industrial partners will help guide the work and ensure its relevance to design practice. This work is timely because the costs of setting up VR based design systems are decreasing (Otto et al, 2005) and should soon be well within the reach of most design consultancies. Also EC technology for design is beginning to reach the stage of maturity where one can envisage how such a complex and multi-facetted domain can be handled although there are some significant challenges to be overcome.

## 5. CONCLUSION

AEC industry designers have to envisage and describe complex prototypes. They do this work for clients who often are unable to read technical drawings and therefore have little idea of what they are actually procuring until it is constructed. Both types of stakeholders would benefit from some form of support. Early design is where all the major decisions are made and yet there are no commercially available tools to support early design decision making. This paper describes a research project which, via a mixture of the development of new technology and the synthesis of existing search and visualisation techniques, should result in an advanced design system to support the early stages of AEC industry conceptual design. The linking of EC search and VR visualisation is seen as being a vital factor. The EC component can be used to find good areas of the design search space which the designers can then use as a starting point to further develop and refine. The combination of computer based support and human control in terms of decision making is another important feature. The authors have started work on the development of the proposed environment and hope to report further in a few years time.

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