This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Improving the utility and value of CAD software for decision-making and design of structural frames

PLEASE CITE THE PUBLISHED VERSION

[http://dx.doi.org/10.1061/40794\(179\)38](http://dx.doi.org/10.1061/40794(179)38)

PUBLISHER

© ASCE

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at:
<https://creativecommons.org/licenses/by-nc-nd/4.0/>

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Soetanto, Robby, Jacqueline Glass, Andrew R.J. Dainty, Andrew D.F. Price, and Tony Thorpe. 2019.
"Improving the Utility and Value of CAD Software for Decision-making and Design of Structural Frames".
figshare. <https://hdl.handle.net/2134/16529>.

IMPROVING THE UTILITY AND VALUE OF CAD SOFTWARE FOR DECISION-MAKING AND DESIGN OF STRUCTURAL FRAMES

R. Soetanto¹, J. Glass², A.R.J. Dainty³, A.D.F. Price⁴, A. Thorpe⁵

ABSTRACT

Three-dimensional modeling and visualization software is increasingly being used by building designers to represent structural frames and communicate design information upstream to their clients and downstream to suppliers/manufacturers. Although design processes and design management have been explored extensively *per se*, the upstream, heuristic decision-making stages of design in relation to 3D software appear to be under-researched. This is understandable because the human side of the process is complex and therefore less straightforward to map. Nevertheless, decisions made early in the project, such as the choice of structural frame, are critical to the project's overall success. Studies of current practice indicate that such decisions tend to be based on heuristic decision-making processes rooted in subjectivity and qualitative reasoning. This paper reports the development of an objective, transparent and systematic selection process that operates effectively within a 3D modeling environment. An innovative framework for simultaneously comparing the performance of a range of structural options against agreed criteria was developed, using the two measures, Importance (I) and Performance (P), which can be used to calculate a Performance Weighted Score (PWS). This framework is a means of assessing 'soft' factors, alongside the conventional cost and time parameters now used in 4D modeling. It thus provides a useful example of a methodology for integrating 'soft' decision making in an otherwise 'hard' software environment.

KEYWORDS

Design; decision making; 3D CAD; human factors; structural frame.

INTRODUCTION

In recent years, construction has been berated for its mediocre performance and apparent inability to provide better value solutions for clients. Various UK government-backed reports

¹ Research Associate, Dept. of Civil and Building Engineering, Loughborough University, Leicestershire, LE11 3TU, UK. E-mail: R.Soetanto@lboro.ac.uk

² Lecturer, Dept. of Civil and Building Engineering, Loughborough University, Leicestershire, LE11 3TU, UK. E-mail: J.Glass@lboro.ac.uk

³ Senior Lecturer, Dept. of Civil and Building Engineering, Loughborough University, Leicestershire, LE11 3TU, UK. E-mail: A.R.J.Dainty@lboro.ac.uk

⁴ Professor, Dept. of Civil and Building Engineering, Loughborough University, Leicestershire, LE11 3TU, UK. E-mail: A.D.F.Price@lboro.ac.uk

⁵ Professor, Head of Department, Dept of Civil and Building Engineering, Loughborough University, Leicestershire, LE11 3TU, UK. E-mail: A.Thorpe@lboro.ac.uk

(Latham, 1994; Egan, 1998; 2002) and initiatives (e.g. Construction Best Practice Programme, Movement for Innovation and Constructing Excellence) have attempted to stimulate performance improvement based on the systematic measurement and benchmarking of effective practice. The industry has also been encouraged to be more innovative and adopt appropriate technology to improve its performance. Many believe that the appropriate use of advanced Information Technology (IT) will help to achieve performance efficiency and effectiveness in the construction process, although evidence suggests that the industry is yet to realize full benefits from IT utilization (Marsh and Flanagan, 2000). Nevertheless, implementation of IT in design areas is seen as promising the most benefits. One of the most significant contributions of IT in the Architectural Engineering and Construction (AEC) industry has been the use of Computer-Aided Design (CAD) for the production of design drawings, which has arguably revolutionized design practice (Debney, 1999). Currently, the use of two-dimensional (2D) CAD systems has achieved maturity level, with all designers using it to a large extent (Sacks et al., 2004a, b). The natural evolution of this technology has been to move towards three-dimensional (3D) software.

Owing to significant progresses made in computing, the last two decades have witnessed a rapid increase in the use of 3D design/modeling tools, such as AutoCAD™ and visualization software such as NavisWorks™. Companies adopting 3D modeling software have found that it can provide them with competitive advantages. For example, 3D software is increasingly being used for marketing and visualization in the housing sector (Whyte et al., 1999) and to develop prototypes within major building construction projects (Whyte, 2003). Linking a 3D model of a building to time parameters (i.e. 4D) allows simulation of construction on site (i.e. virtual construction) and there is a growing trend of integrating project planning software, hence the term 4D CAD (Heesom and Mahdjoubi, 2004). This can be used to improve project scheduling by detecting incomplete and inconsistent schedule activities as well as anticipating potential time-space conflicts and accessibility problems (Koo and Fischer, 2000). There is also an opportunity for integration of 3D modeling systems with various functions within companies, where a change in detailed design can be propagated through other relevant functions, such as estimating, planning and scheduling. The development of an IT-enabled information exchange and sharing system is the logical endpoint to this, but the literature suggests that there is a lack of willingness to share information in practice (Gardner, 1999; Goodwin, 2004; Rivard et al., 2004). Whyte et al. (2002) concluded that a lack of top management support and communication between software developer and end-users inhibited the successful implementation of such modeling systems. Hence, users of the tools need to be aware of appropriate ways to successfully embed tools within existing practices.

3D/4D software is increasingly being used by structural designers to represent structural frames and to communicate design information upstream to their clients and downstream to suppliers/manufacturers (e.g. steel fabricators). The thrust for engineers to use the software is to facilitate a more efficient structural design and analysis process, to produce building design/manufacturing data and visualizations. Main contractors and construction managers also use 3D software for construction programming, coordination and clash detection purposes. These parties derive major commercial benefit from the faster, smoother data

exchange that could take place and the subsequent reduction in the number of and delays caused by requests for information (RFI) and change orders. However, many specialist packages have emerged and there is anecdotal evidence that companies simply cannot support a wide range of software products (both in cost and human resource terms).

This has resulted in the rise of 'industry standard' software packages such as AutoCAD™ and ADT™, which now dominate the market because they are robust and broadly compatible with other software. In trying to improve the efficiency of information exchange within a construction project, the downstream flows from engineer to fabricator and beyond are now reasonably well understood and national/international protocols for interoperability are being developed, such as Industry Foundation Classes (IFCs), Project Information eXchange (PIX Protocol; Goodwin, 2004) and the UK government-funded METIS and AVANTI projects which aim to address the implementation of such protocols. Nonetheless, a major difficulty remains if one wishes to use 3D software upstream to enhance the design decision-making environment. Although design processes and design management have been researched extensively, the relationship and indeed the interface between the upstream, heuristic decision-making stages of design and the downstream, process-based information flows in relation to 3D software appears to be under-researched. This is understandable because the human side of the process is highly complex and therefore less straightforward to map. Nevertheless, some decisions made early in the project, characterized by these heuristic processes, are absolutely critical to the project overall. A good example is selection of an appropriate structural frame.

Studies of current practice suggest that structural frames tend to be selected based on heuristic decision-making processes which are dominated by subjectivity and qualitative reasoning (Ballal and Sher, 2003). Decisions based on familiarity and personal preferences are not uncommon (Idrus and Newman, 2002). Actual selection criteria tend to focus primarily on cost and time requirements (e.g. Idrus and Newman, 2003). Although these two criteria are important and should not be detached from the decision-making process, they are not sufficient to accommodate various issues related to client/user needs and other requirements pertaining to the service-life of the building. For example, there is a growing need to consider added value and design quality (e.g. aesthetics, a building's 'softer' impacts) during the early project stages (Gann et al., 2003). This issue may be made more complicated by the involvement of various stakeholders and consequently affected by their decisions. Cumulatively, project teams can miss opportunities to compare all the viable options for a structure, thus losing the chance to learn useful lessons and widen their choices for structural frames and technologies for future projects. This paper presents the development of an objective, transparent and systematic selection process that operates effectively within a 3D modeling environment. An innovative framework for simultaneously comparing the performance of a range of structural options against predetermined criteria was developed using two measures, Importance (I) and Performance (P), which can be used to calculate a Performance Weighted Score (PWS). This framework is a means of assessing 'soft' factors, alongside the conventional cost and time parameters now used in 4D modeling and so provides a useful example of a methodology for integrating 'soft' decision making in an otherwise 'hard' software environment. The criteria developed in this study represent a synthesis of criteria contained within the existing building performance literature. An

industry survey of these criteria and subsequent factor analysis revealed that they could be grouped under seven dimensions. Used appropriately, the framework could help project teams to better compare alternatives and determine optimal structural frame solutions for given situations, which should enhance the likelihood of achieving better value.

CRITERIA FOR ASSESSING THE POTENTIAL PERFORMANCE OF STRUCTURAL FRAME

Structural Frame Performance Criteria (SFPC) are those that can be used to measure the potential performance of structural frames, performance being defined as the ability of the building to meet its specified requirements throughout its design-life. This broad-based definition encompasses various aspects of the building and is not restricted to structural performance. To assess the structural frame during the early design stages as discussed in this paper, 'potential performance' refers to the likely capability of each frame option to meet the needs of the building and its client. The intention was to compile a list of empirically derived criteria that can be used to assess a number of aspects in relation to the selection of an appropriate structural frame during the early design stages, such as cost, programme and aesthetic considerations. An extensive review of literature was conducted which revealed that there was no authoritative, comprehensive list of performance criteria developed specifically for assessing structural frames. The reviewed literature included building performance evaluations, post-occupancy evaluations and various other construction-related performance indicators (e.g. CIC, 2002; Cohen et al., 2001; KPI Working Group, 2000; Preiser & Schramm, 2002). These were evaluated meticulously for their relevance to structural frames and are presented in Table 1. In total, this examination revealed thirty-one separate criteria that could be used.

The criteria identified have two important characteristics. First, SFPC are relevant to the evaluation of performance of both the physical construction process and the end product (i.e. the building). Secondly, SFPC address both 'hard' and 'soft' issues. The hard criteria include cost and speed of construction that are quantifiable in nature and thus allow more objective assessments to be made. In contrast, the soft criteria comprise more subjective factors relating to individual perceptions around the performance of frame options to meet less tangible design needs. Although the soft factors are difficult to assess, they provide alternative measures to capture the potential value of the structural frame to the client and end-users.

The list of criteria was developed into a questionnaire designed to capture practitioners' perceptions of the relative importance of each criterion. The respondents were asked to rate the importance of the criteria, on a six-point scale ranging from 0 for 'no importance' to 5 for 'extremely important'. The questionnaire was distributed to a selected sample of practitioners at managerial levels, including experienced clients, structural engineers, architects and main contractors. These were based on established contacts and various databases in the public domain. The results revealed that all of the SFPC included in the list were considered to be important, confirming the validity of the criteria as a basis for consideration in structural frame selection (see Soetanto et al., 2004). The data were used to group the criteria using exploratory factor analysis (see Oppenheim, 1992), which yielded seven principal factors. The findings suggest that SFPC could be interpreted using seven underlying performance

dimensions which are ‘physical form and space’, ‘construction process’, ‘long-term sustainability’, ‘establishing confidence’, ‘building impact’, ‘physical appearance’ and ‘client satisfaction’. These provide the basis for the development of a new approach for assessing the performance of structural frames and thus, the selection of the optimal design solution.

ASSESSING STRUCTURAL FRAME OPTIONS

Having compiled and evaluated the SFPC, an important question arose as to how a project team would actually use the criteria in practice. The list of SFPC could be used as a basis for a decision support tool in the selection process, but a mechanism was required in order to ensure that structural frame options could be considered simultaneously. The proposed mechanism firstly requires the ‘importance’ and then the ‘performance’ of a particular frame option to be stipulated against each criterion. These terms are explained below.

IMPORTANCE (I)

During this first process, members of the project team would first need to determine the weighting for each criterion in terms of *Importance (I)*. This indicates the value or weight for each criterion in relation to client and project objectives and their influence on the decision-making process for structural frame selection. The project team needs to consider the importance of the various criteria in terms of meeting client and project objectives and the whole process of design, construction, occupation, maintenance and demolition. The level of importance ranges between 0 to 10, representing a continuum between ‘no importance’ and ‘extremely important’. Here, zero (0) importance indicates the criterion is not related to project objectives and therefore has no impact on the decision (this criterion being subsequently ignored and removed from further calculation). Conversely, an importance value of ten (10) indicates that the criterion is essential in achieving project objectives and hence crucially influences the decision-making process. When rating the importance of one particular criterion, it is crucial to consider the relative importance of the others, thereby avoiding a similar level of importance for all criteria (for example, avoid rating all criteria as extremely important and assigning a score of 10). Prioritization of the criteria into several groups, according to their levels of importance, can help assign reasonable (i.e. workable) importance values for the criteria.

PERFORMANCE (P)

Once the project team has agreed on the *Importance* value for each criterion, the evaluation of structural frame alternatives can commence. Here, the project team needs to assess the performance of one alternative against the criteria regardless their importance. The project team needs to agree on the *Performance (P)* of that alternative for each criterion on a scale of 0 to 10, where 0 means extremely poor and 10 means excellent. The value of *P* indicates how well a particular structural frame scores against a certain aspect of performance. The values of *I* and *P* can then be used to calculate a *Performance Weighted Score (PWS)*, created to integrate the *Importance* values into the assessment, allowing those criteria considered more important to be prioritized accordingly.

PERFORMANCE WEIGHTED SCORE (PWS)

The *PWS* (valued between 0-10) represents a weighted level of structural frame performance, as calculated by the following formula:

$$\sqrt{I \times P}$$

That is, the square root of the product of the level of performance (*P*) and the corresponding level of importance (*I*), as indicated by the project team members. The square root is used to provide meaningful values of *PWS* between 0-10. Hence, a high score represents a high level of weighted performance and vice versa. A higher *PWS* means higher likelihood to achieve client objectives.

The *PWS* for each heading, e.g. *Physical Form and Space*, is the mean *PWS* for that heading based on the number of relevant criteria derived from:

$$\text{Generic PWS} = \frac{\sum^n \sqrt{I \times P}}{n}$$

where *n* = number of criteria attributable to given generic heading.

Hence, in the worked example presented in Table 1, the average *PWS* (in-situ concrete) for *Physical Form and Space* is 5.8 (ranging between 0-10), indicating a reasonable *PWS* for that heading. It should be noted that when a certain criterion is not considered relevant, an importance rating of 0 is allocated and the criterion is subsequently ignored and removed from the calculation.

Finally, the overall *PWS* represents the overall mean total of *PWS* for a particular frame assessment based on the seven headings, i.e. dimensions, which in the example is 5.1 for in-situ concrete frame, representing an average level of *PWS* (in this context ‘average’ is taken as the median value of 5).

ASSESSING STRUCTURAL FRAME OPTIONS: A WORKED EXAMPLE

To demonstrate the use of the framework for selecting an appropriate structural frame, a worked example is presented in Table 1. Suppose that an experienced client from the finance sector is commissioning a new headquarters in a major urban center, such as London. The client appoints an architect well-known for designing commercial buildings. Although there are cost and time constraints, the building should reflect the status and image of the company. Since the building will be designed for a 100 year-service life, whole life cycle issues such as energy efficiency are likely to become more significant in the future. The architect has developed a concept design, but would like to discuss this with other members of the project team regarding form and functional requirements. A meeting is arranged and attended by the client’s representative, architect, structural engineer, quantity surveyor and contractor. The architect presents a concept design for the project. At this stage, it is ideal to

Table 1: Worked Example for Selecting an Appropriate Structural Frame

Performance Criteria	I	In-situ		Steel		Hybrid	
		P	PWS	P	PWS	P	PWS
Physical Form and Space							
The layout, structure and engineering systems are well integrated.	7	5	5.9	6	6.5	7	7.0
The layout and size work well.	6	5	5.5	5	5.5	5	5.5
The circulation works well.	6	6	6.0	6	6.0	6	6.0
The building has sufficient floor to ceiling clear height.	7	7	7.0	7	7.0	7	7.0
The building provides appropriate lettable area/spans.	4	4	4.0	5	4.5	6	4.9
The form is well conceived.	7	6	6.5	4	5.3	9	7.9
Average PWS			5.8		5.8		6.4
Construction Process							
The frame is structurally efficient.	4	3	3.5	8	5.7	7	5.3
The building can be quickly constructed.	4	5	4.5	9	6.0	6	4.9
The construction costs can be minimized.	1	8	2.8	9	3.0	6	2.4
The building has been designed so it can be safely constructed.	7	5	5.9	7	7.0	9	7.9
The overall risk is perceived to be low.	6	3	4.2	5	5.5	7	6.5
Average PWS			4.2		5.4		5.4
Long-term Sustainability							
The building is designed for demolition and recyclability.	6	1	2.4	8	6.9	9	7.3
The building is adaptable to changing needs.	7	6	6.5	8	7.5	7	7.0
The finishes are durable and maintainable.	8	8	8.0	5	6.3	9	8.5
The form and materials optimize the use of thermal mass.	8	2	4.0	1	2.8	9	8.5
The facility management (i.e. O & M, replacement) costs can be minimized.	8	7	7.5	5	6.3	8	8.0
The disposal (i.e. demolition and site clearance) costs can be minimized.	6	1	2.4	5	5.5	8	6.9
The building minimizes environmental impacts (in terms of energy/resource consumptions and waste).	8	5	6.3	2	4.0	9	8.5
Average PWS			5.3		5.6		7.8
Establishing Confidence							
The building enhances the team/client's confidence (in the selected structural frame).	7	1	2.6	5	5.9	9	7.9
The design costs can be minimized.	2	4	2.8	9	4.2	6	3.5
The building is perceived to be simple to build.	5	3	3.9	9	6.7	7	5.9
Average PWS			3.1		5.6		5.8
Building Impact							
The building reinforces the image of the occupier's organization.	9	2	4.2	3	5.2	9	9.0
The building reflects the status of the occupier.	9	3	5.2	2	4.2	9	9.0
The building overall meets perceived needs.	10	3	5.5	4	6.3	8	8.9
Average PWS			5.0		5.3		9.0
Physical Appearance							
The color and texture of materials enhance enjoyment of the building.	8	3	4.9	4	5.7	9	8.5
The quality and presentation of finishes are good.	8	3	4.9	2	4.0	9	8.5
The building overall looks durable.	8	6	6.9	3	4.9	9	8.5
The connections between components are well designed and buildable.	7	-	-	9	7.9	9	7.9
The tolerances of the components are realistic.	7	-	-	8	7.5	9	7.9
Average PWS			5.6		6.0		8.3
Client Satisfaction							
The building provides best value.	10	4	6.3	6	7.7	9	9.5
The client is satisfied with the finished product.	10	5	7.1	5	7.1	9	9.5
Average PWS			6.7		7.4		9.5
OVERALL PWS			5.1		5.8		7.2

use the proposed framework for selecting an appropriate structural frame from a range of alternatives. The team discusses the importance of the criteria and proposes three structural frame alternatives for formal evaluation. These are in-situ concrete, steel and hybrid concrete structural frames (i.e. an innovative combination of precast and in-situ concrete, see Goodchild (1995) and Barrett (2003) for more information). Next, the team evaluates the performance of each alternative against each criterion. Subsequently, the value of *PWS* for each criterion, heading and overall can be calculated.

In this example, the hybrid concrete frame performs better than its alternatives in the prioritized dimensions, resulting in higher *PWS*. Average *PWS* values for ‘building impact’, ‘long-term sustainability’, ‘physical appearance’ and ‘client satisfaction for the hybrid concrete frame are significantly higher than those for in-situ concrete and steel frames. In the ‘construction process’ dimension, the steel frame is quicker and less expensive to build than its alternatives. The hybrid frame scores highly on safety due to off-site fabrication of precast components, resulting in a cleaner, tidier site and less on-site activities. In the ‘establishing confidence’ dimension, a steel frame performs better in terms of design cost and perceived simplicity to build criteria. Overall, based on the *PWS*, the most appropriate structural frame for this hypothetical scenario is hybrid concrete. The steel frame comes second, whereas in-situ concrete frame is the least favorable alternative.

INCORPORATING THE DECISION SUPPORT FRAMEWORK WITHIN A 3D MODELLING ENVIRONMENT

The methodology described can be used to embed the ‘soft’ performance criteria for selecting an appropriate structural frame from several alternatives into a 3D modeling software (e.g. Virtual Reality/VR simulator) via ‘pop-up boxes’ (i.e. windows), as shown in Figure 1. Here, the users are presented with a table of empty cells to fill in with the value of *I* and *P*. The system should then be able to calculate *PWS* automatically for individual criteria, heading and overall frame, allowing the users to consider, discuss and decide which structural frame is the most appropriate for a particular building. This method complements the visual presentation of ‘hard’ criteria of cost and time, thereby helping the users simultaneously consider various aspects of structural frame selection. The simulator also allows any number of additional criteria to be added or excluded from the assessment processes to reflect the bespoke needs of particular clients or other project participants.

To investigate the practical utility of this framework, industry feedback was sought from two case studies and three ‘road show’ interviews. Thirteen industrialists representing contractors, structural engineers, architects, precast manufacturers, lead frame contractors and users, gave their opinions. They responded positively towards the use of a multi-criteria method for selecting an appropriate structural frame. The list of criteria was considered to offer different perspectives on frame selection. They also indicated that because the ‘soft’ performance criteria are more important than harder criteria (time and cost) for some clients or projects, innovative solutions can be scored equitably without perceived risks tipping the balance unfairly. Indeed, if only hard criteria were used then it is unlikely that some concrete solutions (such as hybrid concrete construction) would be selected in most cases as they rarely form the most economical construction solution. Hence, the proposed framework encourages objective and transparent decision-making processes to select an appropriate

structural frame based on an evaluation of the full range of performance criteria. It offers a clear methodology, an inclusive approach and an auditable procedure that design teams can utilize on any project type.

Soft Performance Form 1 of 3

Performance Criteria	Hybrid			Alt. 1		Alt. 2	
	I	P	PWS	P	PWS	P	PWS
Physical form and Space							
The layout, struct. and eng. systems are well integrated.	9	5	4.5	5	3.5	3	4.5
The layout and size work well.	4	3	1.2	5	3	3	1.5
The circulation w...							
The circulation w...							
The building has...							
The building prov...							
The form is well...							

Soft Performance Form 2 of 3

Performance Criteria	I	Hybrid		Alt. 1		Alt. 2	
		P	PWS	P	PWS	P	PWS
Long-term Sustainability							
The building is designed f...							
The building is adaptable...							
The finishes are durable...							
The form and materials u...							
The facility management...							
The disposal costs can b...							
The building minimises e...							
Establishing Confidence							
The building enhances th...							
The design costs can be...							
The building is perceived...							

Soft Performance Form 3 of 3

Performance Criteria	I	Hybrid		Alt. 1		Alt. 2	
		P	PWS	P	PWS	P	PWS
Building Impact							
The bid reinforces the image of the occupier's org'n.	9	5	4.5	5	3.5	3	4.5
The building reflects the status of the occupier.	9	5	4.5	5	3.5	3	4.5
The building overall meets perceived needs.	10	5	5.0	5	3.5	3	4.5
Average PWS			3.89		3.79		4.81
Physical							
The colour and texture enhance enjoyment of the bld.	9	5	4.5	5	3.5	3	4.5
The quality and presentation of finishes are good.	9	5	4.5	5	3.5	3	4.5
The building overall looks durable.	10	5	5.0	5	3.5	3	4.5
The construction low comp. are well des. and buildable.	9	5	4.5	5	3.5	3	4.5
The tolerances of the components are realistic.	9	5	4.5	5	3.5	3	4.5
Average PWS			3.8		2.77		3.73
Client Satisfaction							
The building provides best value.	9	5	4.5	5	3.5	3	4.5
The client is satisfied with the finished product.	9	5	4.5	5	3.5	3	4.5
Average PWS			1.93		2.93		1.93
OVERALL PWS			3.97		3.71		4.08

Buttons: **Calculate**, **Close Windows**

Figure 1: Windows for incorporating soft performance criteria assessment within a 3D modeling software

CONCLUSIONS

Despite the increasing use of 3D/4D software to represent structural frames and to communicate design information upstream to their clients and downstream to suppliers/manufacturers, the relationship and the interface between the upstream, heuristic decision-making processes and the downstream, process-based information flows in relation to 3D software seem to be unclear. However, decisions made early in the project are critical to the overall success of the project, and particularly the decision on the structural frame process. This paper has reported the development of an objective, transparent and systematic selection process that operates effectively within a 3D modeling environment. An innovative framework for simultaneously comparing the performance of a range of structural options against predetermined criteria was developed using two measures, Importance (I) and Performance (P), which can be used to calculate a Performance Weighted Score (PWS). This

framework is a means of assessing 'soft' factors, alongside the conventional cost and time parameters now used in 4D modeling and so provides a useful example of a methodology for integrating 'soft' decision making in an otherwise 'hard' software environment.

The framework could be used during a project meeting where team members are allowed to communicate, discuss and rethink their ideas. The actual 'scores' derived from the assessment framework themselves are not critical, as the framework essentially serves as a guide to discuss various performance issues and integrate the various views of stakeholders. The criteria provide a reference for this exercise and specifically, a basis for assessing (i.e. discussing) advantages and disadvantages of structural frame options. It remains crucial, however, that the team members adopt a proactive and cooperative attitude in dealing with other members and willingly appreciate their ideas, without the presence of a hidden agenda, so that the optimum solution can be achieved to the benefit of all project stakeholders, especially the client. Failure to adopt such a collaborative attitude will undermine the benefits derived from the framework.

Further investigation of decision-making practices in the early design stages is needed, but more specific research should examine the use of 3D/4D software for structural frame design and construction, in relation to issues at the interface between upstream heuristic-based design decision making and downstream process-based information flows. This would improve performance and added value of building through:

- better informed critical design decisions regarding major building elements such as the structural frame;
- a more effective use of technology upstream for these decisions;
- a more effective exchange of early design-based information, which tends to be based on heuristics and as such is incompatible with 3D/4D design technology; and
- a more transparent decision-making process, which allows all possible solutions to be thoroughly evaluated.

ACKNOWLEDGEMENTS

The 'Simulating the performance of hybrid concrete structures using virtual prototyping techniques' project was funded by the EPSRC and this support is gratefully acknowledged. The academic team consisted of the University of Salford, Loughborough University and the University of Wolverhampton. The nine collaborating firms were ABC Structures, British Precast Concrete Federation, Computer Sciences Corporation (CSC), the Concrete Centre (formerly Reinforced Concrete Council), Curtins Consulting Engineers, Edmund Nuttall, HBG Construction, Trent Precast Concrete Ltd, Whitby Bird and Partners.

REFERENCES

- Ballal, T.M.A. and Sher, W.D. (2003). "Artificial Neural Network for the Selection of Buildable Structural Systems." *Engineering, Construction and Architectural Management*, 10(4), 263-271.
- Barrett, P. (2003). "Hybrid Concrete: Improved Processes and Performance." *Proceedings of the Institution of Civil Engineers, Structures and Buildings*, 156(SB2), 193-203.

- CIC (2002). *Design Quality Indicator Questionnaire*. Construction Industry Council, London.
- Cohen, R., Standeven, M., Bordass, B. and Leaman, A. (2001). "Assessing Building Performance in Use 1: the Probe Process." *Building Research and Information*, 29(2), 85-102.
- Debney, P.M. (1999). "CAD – Today is Only Just the Beginning." *The Structural Engineer*, 77(3), 16-20.
- Egan, J. (1998). *Rethinking Construction*. The report of the Construction Task Force on the scope for improving quality and efficiency in UK construction, Department of the Environment, Transport and the Regions, London.
- Egan, J. (2002). *Accelerating Change*. A report by Strategic Forum for Construction chaired by Sir John Egan.
- Gann, D.M., Salter, A.J. and Whyte, J.K. (2003). "Design Quality Indicator as a Tool for Thinking." *Building Research and Information*, 31(5), 318-333.
- Gardner, P.J. (1999). "IT in Engineering Consultancies." *The Structural Engineer*, 77(3), 13-15.
- Goodchild, C.H. (1995). *Hybrid Concrete Construction: Combining Structural Materials for Speed, Quality and Economy in Buildings*. British Cement Association, Berkshire.
- Goodwin, P.W. (2004). *PIX Protocol Guide and Toolkit*. The Building Centre Trust, London.
- Heesom, D. and Mahdjoubi, L. (2004). "Trends of 4D CAD Applications for Construction Planning." *Construction Management and Economics*, 22(2), 171-182.
- Idrus, A.B. and Newman, J.B. (2002). "Construction Related Factors Influencing the Choice of Concrete Floor Systems." *Construction Management and Economics*, 20, 13-19.
- Idrus, A. and Newman, J. (2003). "IFESS: a Computer Tool to Aid Structural Engineers at the Conceptual Design Stage." *Construction Innovation*, 3, 127-143.
- Koo, B. and Fischer, M. (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.
- KPI Working Group (2000). *KPI Report for the Minister for Construction*. Department of the Environment, Transport and the Regions, London.
- Latham, M. (1994). *Constructing the Team*. Final report of the government/industry review of procurement and contractual arrangements in the United Kingdom construction industry, HMSO, Department of Environment, London.
- Marsh, L. and Flanagan, R. (2000). "Measuring the Costs and Benefits of Information Technology in Construction." *Engineering, Construction and Architectural Management*, 7(4), 423-435.
- Oppenheim, A.N. (1992). *Questionnaire Design, Interviewing and Attitude Measurement*. Pinter, London.
- Preiser, W.F.E. and Schramm, U. (2002). "Intelligent Office Building Performance Evaluation." *Facilities*, 20(7/8), 279-287.
- Rivard, H., Froese, T., Waugh, L.M., El-Diraby, T., Mora, R., Torres, H., Gill, S.M. and O'Reilly, T. (2004). "Case Studies on the Use of Information Technology in the Canadian Construction Industry." *Electronic Journal of Information Technology in Construction*, 9, 19-34.

- Sacks, R., Eastman, C.M. and Lee, G. (2004a). "Parametric 3D Modeling in Building Construction with Examples from Precast Concrete." *Automation in Construction*, 13, 291-312.
- Sacks, R., Eastman, C.M. and Lee, G. (2004b). "Process Model Perspectives on Management and Engineering Procedures in the Precast/Prestressed Concrete Industry." *Journal of Construction Engineering and Management*, 130(2), 206-215.
- Soetanto, R. Dainty, A.R.J., Glass, J. and Price, A.D.F. (2004). "Criteria for Assessing the Potential Performance of Hybrid Concrete Structural Frames." *Engineering, Construction and Architectural Management*, 11(6), 414-425.
- Whyte, J. (2003). "Industrial Applications of Virtual Reality in Architecture and Construction." *Electronic Journal of Information Technology in Construction*, 8, 43-50.
- Whyte, J., Bouchlaghem, N., Thorpe, A. and McCaffer, R. (1999). "A Survey of CAD and Virtual Reality within the House Building Industry." *Engineering, Construction and Architectural Management*, 6(4), 371-379.
- Whyte, J., Bouchlaghem, N. and Thorpe, A. (2002). "IT Implementation in the Construction Organization." *Engineering, Construction and Architectural Management*, 9(5/6), 371-377.