# AN INCLUSIVE AUDITABLE APPROACH TO STRUCTURAL FRAME SELECTION

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## ABSTRACT

The structural frame is an essential element of any large building, influencing its short and long-term performance. Studies of current practice with regards to frame choice indicate that structural frames tend to be selected based on heuristic decision-making processes dominated by subjectivity and qualitative reasoning. This paper reports on the development of a decision support framework aimed at making the process more systematic and transparent. Following a literature review and industry survey, a framework for comparing the performance of structural options against agreed criteria was developed, using two measures, Importance (I) and Performance (P), which can be used to calculate a Performance Weighted Score (PWS). This framework was then incorporated into a Virtual Reality (VR) simulator as a means of assessing 'soft' criteria, alongside cost and programme. The final product is a simple to use and yet highly informative tool that can be used from the earliest concept stage to objectively guide structural frame selection. It was devised to consider the full range of concrete and steel frame options and can be applied to virtually any building type. Initial feedback from industrialists collected through its application on two case studies and demonstration 'road shows' have revealed the tool's capabilities for both informing the frame choice process and ensuring that the most appropriate and best value decision is made with regards to structural frame type.

**Keywords**: decision making; design; performance criteria; project team; structural frame.

## INTRODUCTION

The opportunity to improve the performance and value of a proposed project is significantly greater during early design stages rather than later on in the delivery process. During these stages, various factors and inputs / requirements from project stakeholders should be captured and considered appropriately to ensure high quality decisions. Hence, it is vital that a decision-making framework is provided to enhance the likelihood of achieving high quality results. One of the major decisions that has to be made during early design stages of a building project is the most appropriate structural frame. The structural frame is an essential element of any large multi-storey building. In the short-term, the choice of frame must satisfy the client's immediate project needs, such as construction being completed on time and to budget. In the long-term, it must permit, for example, a degree of flexibility to accommodate future re-use of the building. The final choice is of particular significance since the frame interfaces with many of the other elements of the building, thereby influencing their specification and buildability.

Despite the importance of early stage decisions, 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). Here, decision makers (e.g. architects, engineers) who have extensive experience in structural frame design, frequently appear to hold pre-conceived ideas of which structural frames (e.g. materials and their combinations) are the most appropriate for particular building types, shapes or budgets. Actual selection criteria tend to focus primarily on cost and time requirements (e.g. Idrus and Newman, 2003; Gunaydin and Dogan, 2004). 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; Thomson *et al*., 2003). This issue may be made 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. Ultimately, this could hamper performance improvement and delivery of value to the satisfaction of construction clients.

This paper describes the development of an objective and transparent decision support framework for the appropriate selection of structural frame materials. To ensure an objective and transparent structural frame selection process, the framework includes an authoritative list of performance criteria and the means for open discussion among the main project team participants (i.e. client, design team and constructors). It is also flexible enough to be supplemented by additional criteria, bespoke to a particular project's requirements. This framework has the potential to improve team learning and result in buildings with a higher value for the client. A robust set of 'hard' and 'soft' criteria which together may better capture the potential 'value' of structural frames, as opposed to the traditional outturn measures of time and cost, has been included. This would help to realise the potential benefits of using innovative structural frame technologies, such as hybrid concrete (an innovative combination of precast and in-situ concrete, see Goodchild (1995, 2001) and Barrett (2003) for more information). The criteria developed in this study were compiled based on a thorough review of building performance literature. An industry survey of these criteria and subsequent factor analysis revealed that they could be grouped under seven dimensions. The framework offers a systematic evaluation of the importance of each criterion and the likely performance achieved using various structural frame options. 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 Kim and Mueller, 1978a; 1978b; 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.

## THE ASSESSMENT OF STRUCTURAL FRAMES

Having compiled and evaluated the SFPC, an important question arose as to how a project team would actually utilise 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 as follows.

### 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 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). Prioritisation 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 prioritised 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:

$$\sqrt{\mathrm{IxP}}$$

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. 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:

$$\text{Generic PWS} = \frac{\sum^{n} \sqrt{\text{IxP}}}{n}$$

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. Note, 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 alternatives: a worked example**

To demonstrate the use of the tool 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 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 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. 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.

## 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 minimised. | 1 | 8 | 2.8 | 9 | 3.0 | 6 | 2.4 |
| The building has been designed so it can be safety 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 optimise 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 minimised. | 8 | 7 | 7.5 | 5 | 6.3 | 8 | 8.0 |
| The disposal (i.e. demolition and site clearance) costs can be minimised. | 6 | 1 | 2.4 | 5 | 5.5 | 8 | 6.9 |
| The building minimises 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 minimised. | 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 organisation. | 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 colour 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*** |

In this example, the hybrid concrete frame performs better than its alternatives in the highly prioritised 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 favourable alternative.

## INCORPORATING THE DECISION SUPPORT FRAMEWORK WITHIN A VIRTUAL REALITY SIMULATOR

The methodology described can be used to embed the ‘soft’ performance criteria for selecting an appropriate structural frame from several alternatives into a 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 of frame selection. They also indicated that the ‘soft’ performance criteria are often more important than harder criteria (time and cost) for the adoption of high quality structural frame solutions such as hybrid concrete. Indeed, if only hard criteria were used then it is unlikely that hybrid concrete solutions would be selected in most cases. 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 utilise on any project type.

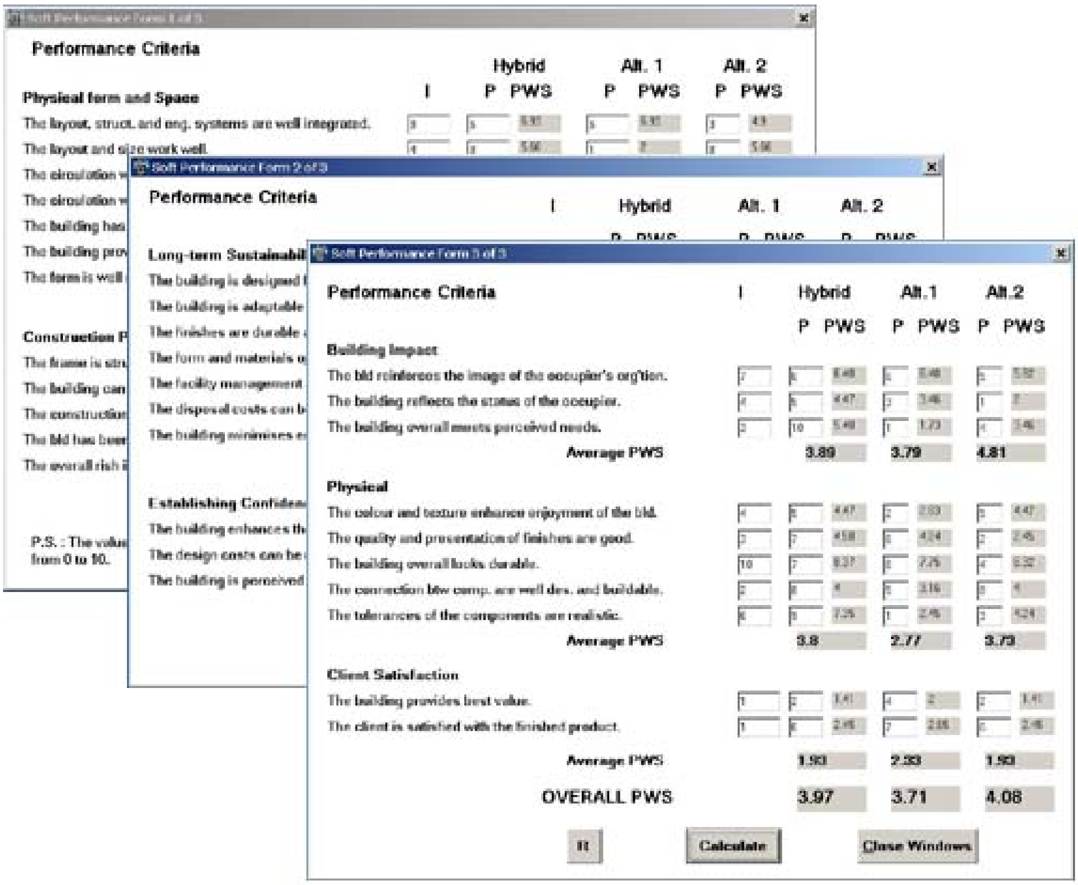


**Figure 1 Windows for incorporating soft performance criteria assessment within a virtual reality simulator**

## CONCLUSIONS

This paper has presented a decision support framework to provide a robust and transparent methodology for informing frame choice. To ensure an objective and transparent structural frame selection process, the framework includes an authoritative list of performance criteria and the means for open discussion among the main project team participants (i.e. client, design team and constructors) during the selection processes (i.e. option study sessions). It requires the project team to determine the weighting of each criterion, i.e. the *Importance* (*I*) and the *Performance* (*P*) of a particular structural frame against each criterion. The level of importance indicates the value or weight for each criterion in relation to client and project objectives, and in influencing the decision of selecting appropriate structural frame for a particular building project. The value of *P* indicates how well a particular structural frame performs against a certain criterion. To integrate the importance values into the assessment, a *Performance Weighted Score* (*PWS*) is created. The *PWS* is then used to calculate scores in each criterion, each heading and overall structural frame performance. *PWS* provides the basis to select an appropriate structural frame for that particular building project. This methodology was incorporated as one main element of a virtual reality-based simulator which also includes the capability to review hard criteria. Initial evidence of the practical utility of the framework based on the opinions of thirteen practitioners suggested that the use of a multi-criteria method was relevant, and that the proposed framework would encourage objective and transparent decision making processes, highlighting the importance of a meeting where key participants can discuss the selection criteria and agree on the scores of importance and performance, and finally select an appropriate solution.

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.

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