Enabling Technologies in Integrating Design and Construction

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Abstract
This paper focuses on the role of the IT tools that have enabled the development of a decision support system, the Integrated Design System (IDS). The IDS facilitates the derivation of production related designs for structural steelwork, by integrating the information flow from each of the existing processes. It will enable the designer to investigate the effects of conceptual decisions on fabrication, transportation, and erection costs, and assess the constructability of designs, providing advice on feasible and economic alternatives. This has beneficial implications for the overall economy and constructability of the finished design.

Keywords: Decision Support; Reengineering; Integration; Steelwork; IT Tools;

INTRODUCTION

The development and application of Information Technology(IT), has had a profound effect on society, supporting the development of new ways of working, communicating, and being entertained. In the construction industry, computers support visualisation, planning, management and a host of other functions, which is enabling the industry to change its culture, tackle deficiencies in business processes, and improve competitiveness and productivity. As part of this “process of change”, the authors are collaborating with UK industry in a funded research project aimed at reengineering the process of steel construction.

The structural steelwork construction process in the UK (Figure 1), is made up of three distinct components, design, fabrication, and erection, which are relatively independent of each other. However whilst chronologically discrete, decisions made in the upstream activities may, and frequently do, constrain the downstream activities, often with adverse results. For instance, designers focus on producing a structurally adequate frame, selecting adequate section sizes from a design viewpoint, and paying less attention to the member connections and details. This can adversely affect the overall construction costs, as the designed sections may require expensive connections during fabrication, or additional bracing during erection (SCI, 1992).

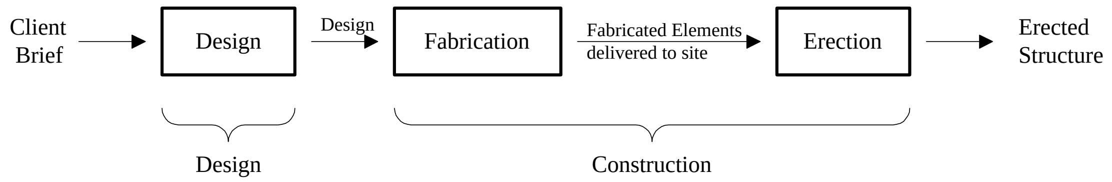

Figure 1: The Steel Construction Process

The steel construction process would thus benefit from the reengineering of its components, so that decisions regarding structural adequacy, and practical and cost effective fabrication and erection can be taken concurrently. As a first step in reengineering the processes of steel construction, the authors are integrating the information flows from each of the existing processes, through the development of a decision support system, the Integrated Design System (IDS). The IDS will facilitate a design process, where decisions made, simultaneously takes into account their effect on the fabrication and erection stages. The reengineered process, moves away from the traditional fragmented procedure towards a more integrated procedure, whereby designers have a greater appreciation of the other processes. This is essential if truly competitive designs with implications for profitability and better value for money for clients are to be produced.

This paper examines the role of the key IT tools - object oriented design, cost modelling, embedded knowledge based systems and decision support - that have been employed in the development of the decision support system. As a prototype investigation for all forms of steel construction, the project has adopted as its main structural form, long span tubular three dimensional trusses, using circular or rectangular hollow sections solely or in combination, with the option to use open sections as chords. Tubular trusses are particularly sensitive to design decisions, as the cost of the joints form a significant part of the total cost, and minimum weight solutions can be quite misleading.

OBJECT ORIENTED DESIGN

The object oriented approach to software development, attempts to manage the complexity inherent in real-world problems by abstracting out knowledge and encapsulating it within “objects” (Wirfs-Brock et al, 1990). Objects are entities that consists of information and operations that can act on the information contained, and make it available to other objects. For example, a member object would be able to compute its length, store the results, and on request make it available to a member design object, for inclusion in the calculation procedure. An object oriented design thus decomposes a system into entities which have defined responsibilities, and accomplish work through a series of request from one object to another, to perform an operation, reveal some information, or both. The object oriented paradigm encourages a view of the world as a system of co-operating and collaborating agents. This has formed the basis for the development of the IDS which consists of a number of modules, responsible for analysis, design, costing and advice (Figure 2).

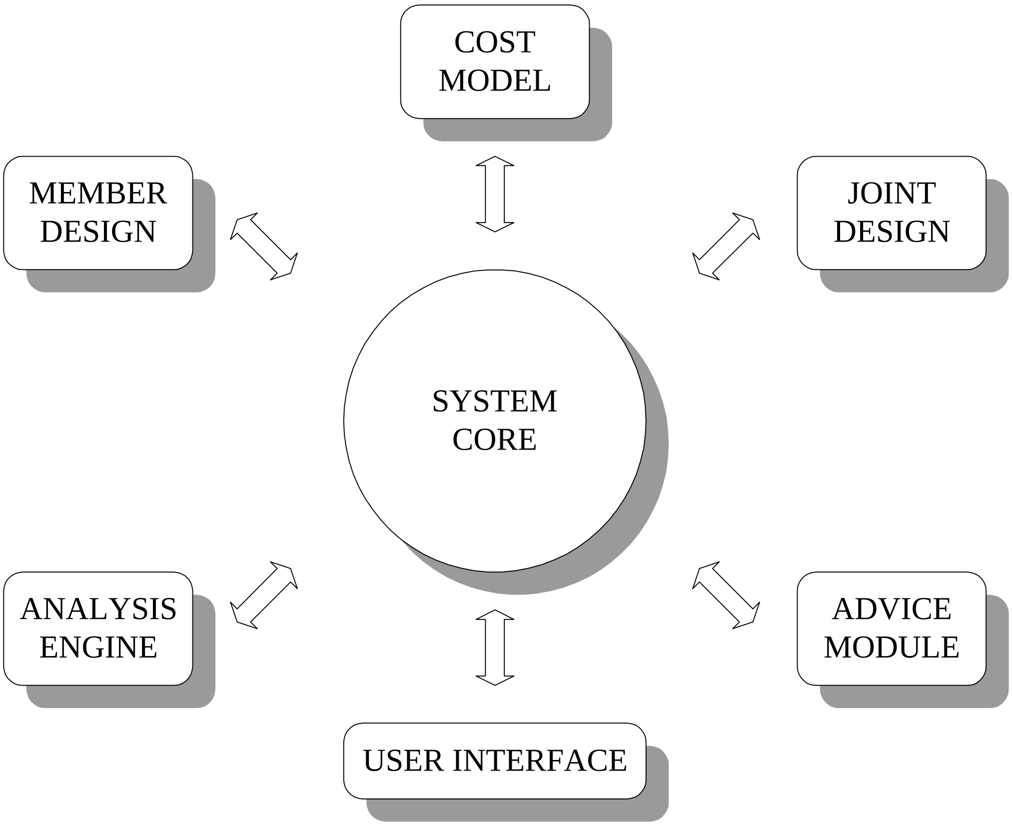

Figure 2: Schematic Representation of the IDS

Central to the IDS, is the System Core that serves as the central processing unit, routing requests and replies between the user interface, itself, and the various modules that comprise the system. It consists of an information structure, implemented as an object hierarchy that represents the truss and associated data, such as nodes, elements, joints, members, loading, restraints, and sections, as well as a system database, which comprises a section database, material database, and cost database. One of the major advantages of adopting an object oriented approach is that for a given object a variety of interfaces (access) to its data can be defined. This has enabled the implementation of the truss object hierarchy, such that it caters for the different data representations, required by the various modules. For instance, the Analysis Engine views the truss as a structure consisting of elements between nodes, whereas the Cost Model views the truss in terms of chords and braces connected by fabrication joints. All modules thus interact with a single data structure, and do not need to make copies, resulting in savings in memory usage and processing time. This has also facilitated the implementation of system-wide concurrency, such that changes made by one module are immediately reflected in another. For example, changing the section size of a member from the Member Design Module, will automatically update the affected joint's capacity in the Joint Design Module, and the cost of the truss in the Cost Model. The System Core maintains the relationships between the various data representations, ensuring consistency of data.

The Analysis Engine is an off-the-shelf package, that forms part of the QSE Space™ structural design package. It communicates with the System Core through the transfer of binary files, which pass analysis data and results. The Member Design Module supports the execution of capacity checks, and design of truss members. It also has, an embedded advice knowledge based system, that can advise on remedial action in the case of failures.

Similarly the Joint Design Module enables capacity checks on joints, and provides advice on practical detailing, and remedial actions in the event of failure. The Cost Model enables the designer to assess the effects of conceptual decisions on fabrication, transportation and erection costs, based on derived costs. While the Advice Module assesses the constructability of designs, providing advice on feasible and economical alternatives. With the exception of the Analysis Engine, all other modules are implemented using objects, which encapsulate the required knowledge, and are stored as extension dynamic link libraries (DLL). Extension DLLs allow full advantage of the object oriented methodology to be taken because, while supporting the modular structure of the IDS, they also facilitate the integration of the modules with the System Core. This is because extension DLLs can export objects, and thus, the System Core for example, can create and interact with an instance of the Member Design Module, as required at runtime.

The IDS is being developed in Windows 95, using Visual C++ v 4.0. , by a research team, split between two research centres. The feasibility of carrying out development at two remote locations, has been largely facilitated by the object oriented design of the IDS. It has also been further supported by the availability of an adequate communication infrastructure, through electronic mail, and the Internet.

COST MODELLING

A model represents some aspect of reality, and may be defined as a representation that possesses some of the features of the system under investigation (Urry, 1991). Modelling aims to facilitate the understanding of a system, and the utilisation of cost models to facilitate the understanding and implications of costs and cash flows is well established. Cost models are employed across a wide range of fields, finding applications in project planning, resource management, product costing, and financial appraisal, among others. The importance of cost models has been emphasised, by the increasing demand for effective and efficient control of cost, as industries strive to improve their efficiency and competitiveness. Furthermore cost is typically the metric by which various project options are assessed.

In the construction industry, cost described as an expenditure, has been defined as the resultant of labour, materials, plant and management deployed for a specific activity, and charged according to the accounting system of an organisation (Seeley, 1996). Fabrication cost is the most difficult component of the overall construction cost of a steel structure to estimate, and is highly influenced by the adopted design details. For example the cost of a connection using a butt weld, could be triple that of one using an equivalent fillet weld (Firkins & Hemphill, 1991). Cost modelling for the steel fabrication process is complicated by the fact that no two jobs are the same, even if they have similar structural forms. Fabricated components are typically non-standard and impose varying work loads in terms of labour and equipment. Furthermore, available cost data is typically based on experience and observation, and is thus subjective and not well defined. Compounding the problem is the fact that no two steel fabricators will cost a job in the same way. Their operations differing in terms of economies of scale, types of equipment, skills, and even type of business sought.

The cost model developed for the IDS, is thus aimed at producing relative costs sensitive to varying work content. Such that designers can readily evaluate alternative design details, and be supported with relative cost information when deciding on a scheme. Working in close collaboration with a leading steel fabricator in the UK, a process-based cost model derived from a steel fabrication business process model (Yusuf & Smith, 1996), is being developed. The model is implemented as an object hierarchy, which encapsulates the various operations the truss must undergo. For instance the object responsible for the procurement of materials, contains the logic required to process the truss and ascertain the cost of the associated sections. Costs are derived from cost data stored in the System Database, which holds all costing information such as, treatment costs, section costs, and costs associated with material preparation and welding. The section costs are based on the current price list of the main supplier of steel sections in the UK, British Steel. While the fabrication costs have been derived with the project's industrial partner. In line with the process based design of the cost model, cost data reflects the cost associated with each activity. For instance surface treatment is costed at a rate per square metre, while the cost of end preparation is based on fabrication hours. This moves away from the traditional method of costing structural steelwork as a rate per tonne, which can be misleading as it does not reflect actual work content, and encourages optimisation based on tonnage, which may not necessarily be advantageous (Watson et al, 1994). In comparison, the method of costing adopted, enables the designer to ascertain how and where design decisions affect cost.

The cost model supports costing at the joint and truss level facilitating the comparison of alternative details or alternative truss schemes. The cost model is being further developed to consider the transportation and erection of the truss.

EMBEDDED KNOWLEDGE BASED EXPERT SYSTEMS

Knowledge based expert systems (KBES), are computer programs that can manipulate knowledge as well as data. By applying logical deduction and induction processes, KBES are able to reason with this knowledge and make inferences as to what actions to take or what conclusions to reach. They can be used to represent human expertise (knowledge) in a particular domain, and manipulate this knowledge to solve problems or give advice.

Despite extensive research into the development of KBES, as evidenced by literature, the uptake of KBES as practical tools has been relatively low. The authors in other work (Nethercot & Tizani, 1996), have attributed this to the fact that much of the research work has focused on testing the applicability of this technology to solving engineering problems, rather than on delivering solutions to problems that address the needs of the industry. Furthermore KBES still suffer from the "hype" that surrounded their conception, which encouraged the view that they could replace the human expert. This resulted in a general distrust of KBES by designers, who are sceptical that the subtleties and intricacies of their decision making can be carried out by a computerised system. It was observed that an emerging trend, whereby "intelligent systems" were embedded within everyday software, acting in a supportive role, would make KBES accessible and acceptable to the practising engineer.

In line with this trend the IDS, has three KBES embedded within the system. In the Member Design and Joint Design Modules, the embedded KBES, provide advice in the event of a member or joint failing structurally. By analysing capacity results to determine the mode of failure, the KBES are able to utilise knowledge stored as rules, to advise on remedial action. For instance computation of, and advice on, limiting values in response to a validity violation during a joint capacity check. The third KBES embedded within the IDS forms the Advice Module, which has prime responsibility for assessing the constructability of designs, and providing advice on feasible and economical alternatives. It examines the layout of the truss and fit up of its members, highlighting features that may adversely affect cost, or contravene common design practice. For example the presence of overlap joints, the presence of a large number of varying section sizes, or arrangements that involve high or low brace angles.

Knowledge acquisition for the rules that make up the KBES, has involved structured interviews with the industrial partners and other practitioners. The KBES are being implemented using ILOG Rules™, which supports the encapsulation and manipulation of rules within C^{++} objects.

DECISION SUPPORT

In identifying the role of decision support systems, Bonczek et al (1981) states that:

"*The human investigates in the decision-making process and during this investigation the computer supports the process by furnishing pertinent information, thus creating a human-computer decision making system*"

The IDS has been designed to meet this defined role, furnishing the designer with pertinent information, related to assessing the effects of the design on the fabrication and erection process. Through a task oriented graphical user interface, the IDS integrates the information flows of the design and construction stages, allowing the designer to define a structure, investigate its structural adequacy, ascertain costs, derive alternatives, compare, and commit to one or the other, in a totally seamless manner.

To demonstrate how the IDS enables the designer to adopt this improved way of working, consider the case where the designer has just carried out a joint capacity check. The joint strength fails, and designer decides to investigate options available. A request for advice, responds with the suggestion that the designer consider reducing the gap between braces, increase the chord thickness or brace diameter, as a last resort the systems suggests that stiffening of the joint could also be considered. A what-if scenario ensues where the designer opts for an increase in brace diameter, effects the change, and the joint configuration is automatically computed, all relevant member and joint capacities, and associated costs updated, and the designer is furnished with the new results. The joint passes, but consideration of the entire truss reveals that a number of similar joints are failing along the chord. The designer then decides to compare the cost of similarly increasing the brace diameters, or simply changing the chord thickness. At the end of the investigation the designer opts for increasing the chord thickness, and commits the change to the design.

The above scenario illustrates how the IDS provides decision support during the design process. The provision of a joint checking facility, in itself, plays a particularly important role in integrating design with construction, as joint checks are typically carried out by the fabricator, at which time the design has been finalised and material already ordered. Joint failure at this stage usually results in expensive remedial operations, such as stiffening being required. In furnishing the designer with pertinent information, the IDS adopts a hierarchical approach, enabling the user to control the level of detail required to support decision making. For example, in executing member capacity checks, the user can elect to respond immediately to the “pass” or “fail” message, or seek detailed results and advice. This helps prevent a situation whereby the designer is overloaded with data, and re-emphasises the decision support role of the IDS.

FINDINGS

The Integrated Design System(IDS) is a decision support system that demonstrates the practicality of integrating the information flows from the design, fabrication and erection stages. The IDS can be thus be used by the designer, to support the making of decisions, that take into consideration their influence on the other stages.

The object oriented design of the system, has supported the implementation of efficient interaction between the various modules, and the inclusion of system-wide concurrency through the use of a single data structure. The cost model developed, provides relative costs sensitive to varying work content, allowing the designer to assess the influence of design decisions on cost. The process based methodology adopted, ensures that the designer can ascertain how and where design decisions affect cost. Embedded knowledge based systems have provided a means by which the IDS can complement the engineering knowledge of the designer, and aid in the making of informed decisions. The system has been designed in accordance with the principles of decision support, and furnishes pertinent information, as and where required, in aid of the design process.

Although it is no panacea, the IDS facilitates an improved way of working, through the strategic integration of design and construction, using as a specific example long span tubular trusses. Such integration will realise significant improvements in efficiency and cost effectiveness, with beneficial implications for all parties involved, clients, designers, fabricators and erectors. This is a first step in the much needed re-engineering of the steel construction process, and the principles established will be applicable to other forms of construction.

ACKNOWLEDGEMENTS

The research project is being conducted under the LINK-IDAC (Integrated Design and Construction) programme, jointly funded by the Engineering and Physical Sciences Research Council (EPSRC), Department of Environment (DOE), and UK industry. The authors wish to acknowledge the financial support of the EPSRC and DOE, and the contributions of the industrial partners in the research programme; namely British Steel Tubes & Pipes, Ove Arup & Partners, Watson Steel Limited and QSE Limited.

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