PROCEEDINGS OF THE
THIRD INTERNATIONAL CONFERENCE ON
CONCURRENT ENGINEERING IN CONSTRUCTION

Iris D. Tommelein, Editor

1-2 JULY 2002
Aims of the Conference

The aim of the conference is to engender Concurrent Engineering thinking and practices within the architecture/engineering/construction industry. The conference is to provide an international forum for researchers and leading experts from various disciplines to exchange ideas and disseminate information on latest developments in Concurrent Engineering.

"Concurrent engineering is a systematic approach to the integrated, concurrent design of products and related processes, including manufacture and support. This approach is intended to cause developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements" [Winner et al. 1988]

Conference Themes

The overall conference theme is "Concurrent Engineering in Construction" but this covers many subjects. Topics of interest for presentation and discussion include but are not limited to:

- Foundations and principles of CE
- Process and enterprise modeling
- Information management & technologies
- CE environments
- Applications and tools
- Industry case studies and experiences
- On-going and recent research projects CE
- Methods and Tools for Teaching Concurrent Engineering
Background

The First International Conference on Concurrent Engineering in Construction - CEC97 - was hosted by the Institution of Structural Engineers and held in London, UK, in 1997.

A group of researchers established CIB Task Group 33 in February 1998 to further pursue the theory and practice of concurrent engineering in construction. TG33 is part of CE-NET, the Concurrent Engineering NETwork of excellence. The TG33 website is posted at http://cic.vtt.fi/cib_tg33/index.html.

The Second International Conference on Concurrent Engineering in Construction - CEC99 - was organized by CIB TG33 and VTT and held in Espoo, Finland on 25-27 August 1999. The conference website still is available at http://cic.vtt.fi/cec99/ and it includes conference abstracts.

Organizing Committee

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Members of the Organizing Committee and members of the International Technical Advisory Board handled the single-blind peer review process of all submitted papers.
On-line Conference Proceedings

The conference web site address is http://www.ce.berkeley.edu/~tommelein/concur02. A conference agenda and on-line abstracts will be posted on this page.

Acknowledgments

I owe many thanks to all authors, reviewers, conference co-organizers, and participants for making this conference a success.

Iris Tommelein, Editor
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ATTRIBUTES THAT A/E NEED TO UNDERTAKE CONCURRENT ENGINEERING

Florence Y.Y. Ling¹

ABSTRACT
Concurrent engineering is widely practised in design-build (DB) projects. In order to ensure concurrent engineering proceeds smoothly, it is important to put in place A/E who possess the ‘right’ attributes. The purpose of this study is to identify the attributes that design-builders consider when they select architects and engineers (A/E) to handle DB projects and undertake concurrent engineering (CE). Data were collected via mailed standard questionnaire from design-builders. For comparison, data were also collected from A/E.

From the point of view of design-builders, the most important attributes are the A/E’s job knowledge in economical design, constructability and regulations that are relevant to the project. In addition, they must have good problem solving ability and project approach. It is not necessary for A/E to belong to a large firm. On the other hand, many attributes which design-builders feel are important, have not been given the same level of importance by A/E. These include having a manageable level of workload, and having the necessary job experience. It is recommended that A/E take note of these attributes, in order that they could be engaged in projects involving CE.

KEY WORDS
Task performance, general mental ability, job knowledge, task proficiency, job experience, concurrent engineering, design-build.

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INTRODUCTION

Concurrent engineering (CE) is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support (Winner 1988). Developers therefore need to consider, from the outset, all elements of the product life-cycle from conception through disposal. Eppinger (1994) identified the need for CE in large projects that need collaboration of interdependent tasks. The performance of these tasks is dependent on upstream production reliability and downstream task sensitivity. With CE, a reliable upstream production could be ensured. This minimizes the mistakes that could lead to extensive rework downstream as a result of erroneous upstream work. CE could also lead to downstream tasks that are less sensitive to errors made upstream, so that downstream work could be started early, to gain a significant duration reduction, while generating relatively little rework as a result of errors made upstream (Pena-Mora and Li 2001). A major feature of CE is effective integration of all aspects of product development, by performing simultaneously a variety of activities that used to be done sequentially (Jo et al. 1993).

Studies have shown that one of the ways of applying CE to construction is through design-build (DB) procurement system (Love et al. 1998; Gunasekaran and Love 1998; Anumba and Evbuomwan 1997). Love et al. (1998) proposed a model demonstrating how CE can contribute to project effectiveness through a multi-disciplinary project team in a DB environment. They concluded that the introduction of CE approach is not radically different from DB, but the fundamental difference lies in the composition of the design team and the reliance on teamwork. Pena-Mora and Li (2001) developed a dynamic model to plan and control DB projects. The model is underpinned by, among others, CE concepts. Anumba and Evbuomwan (1997) proposed a process model to facilitate the concurrent development in DB process through the integration of all project participants into a multi-functional matrix team capable of solving potential downstream problems early in the project life-cycle and the adoption of CE design system.

The above studies show that DB and CE potentially have a lot in common. The aim of this paper is to investigate the attributes that architects and engineers (A/E) should possess to undertake CE, in the context of DB projects. The attributes are investigated through the Theory of Task Performance (Schmidt et al. 1986). The specific objectives of the paper are to:

- Identify attributes that A/E should possess to undertake CE in DB projects
- Compare the views of A/E and design-builders on the attributes needed to undertake CE and DB.

The fieldwork for this paper was carried out in Singapore. In Singapore, the Building and Construction Authority (2002) defines DB as a type of procurement method whereby the owner enters into a single contract with one entity who is responsible for both the architectural/engineering and construction works of the project. The owner usually approaches a contractor or a small group of pre-selected contractors at an early stage of the project. The contractors, together with their team of architectural and engineering consultants will propose an outline design and cost based on the owner’s requirements. Depending on the
type of project, the owners may engage their own consultants to assist them in the preparation of a more detailed design brief and tender specification. The successful contractor will be fully responsible for both the design and construction works of the project and the owner needs to deal only with the successful contractor.

The importance of this study is that significant A/E attributes to undertake CE are identified. Clients and design-builders could rely on these to select the ‘right’ A/E. Selecting the right A/E will ensure that a satisfactory facility is designed, drawings are completed in a timely manner, and minimal time is needed to monitor and manage them. These lead to a greater chance of project success.

This study is relevant to two groups of construction industry participants; contractors and A/E. For the A/E, as their requisite attributes are identified, they can now go about acquiring them. If they already possess these attributes, this study highlights the more relevant and important attributes that clients expect of them, especially to undertake CE. By possessing these attributes, they will be able to better satisfy clients, and repeat orders may then be expected. Contractors who intend to venture into DB projects and undertake CE could use the findings of this study to assist them in selecting A/E.

In this paper, the likely attributes are first identified. The relevance of these identified attributes are tested in the fieldwork, and the results are presented and discussed. The final section discusses the limitations and concludes the study.

THEORETICAL FRAMEWORK

The attributes that A/E need to possess to undertake CE is investigated through the Theory of Job Performance (Hunter 1983; Schmidt et al. 1986). This theory is selected because one of the most important factors that should be considered when selecting A/E is their ability to perform in the job, and this theory explains the criteria that contribute to good task performance. According to the Theory of Job Performance, there are four main criteria that contribute to task performance: general mental ability, job knowledge, task proficiency, and job experience. These criteria, with particular reference to A/E who undertake CE, are now operationalized and discussed.

GENERAL MENTAL ABILITY

General mental ability, also known as cognitive ability, is a good predictor of job performance because individuals need general mental ability to:

- carry out tasks, especially complex tasks (Schmidt et al. 1986)
- learn how to undertake the task (Hunter and Schmidt 1989)
- have creativity, achievement motivation, leadership, social skills, health, and fitness (Ree and Earles 1993)
- reason out and plan their jobs, ensuring that the work would be done speedily and smoothly (Hunter 1983)
acquire job knowledge which is required to perform the work efficiently and excellently (Hunter 1983).

In selecting A/E to undertake CE in DB, two skills are identified under the criterion labeled as ‘general mental ability’:

- A/E is creative and innovative (H1.1)
- A/E has good problem solving ability and project approach (H1.2).

**JOB KNOWLEDGE**

Job knowledge has been found to influence job performance (Ree et al. 1995). Job knowledge comprises ‘knowledge of technical information about objects and concepts required to do the job’ and ‘knowledge of processes and judgmental criteria required for efficient or correct action on the job’ (Hunter 1983). Job knowledge is an important criterion for job performance because individuals with more job knowledge are more efficient as compared to those with insufficient job knowledge who would waste time looking up the information or taking time away from supervisors or co-workers when asking them for help, and are also more prone to commit errors in their work (Hunter 1983).

Based on the above discussion, four attributes are identified under the criterion labeled as ‘job knowledge’:

- A/E has good knowledge of economical design (H2.1)
- A/E has good knowledge of constructability (H2.2)
- A/E has good knowledge of design and regulations which are relevant to the project (H2.3)

**TASK PROFICIENCY**

Task proficiency is also known as technical proficiency, technical ability, competence, and skill. The selection of A/E for technical proficiency may be based on four aspects of quality: technical quality, functional quality, workmanship quality, and architectural quality (Pain and Bennett 1988). Technical quality and functional quality can be used to gauge the quality of A/E’s design at the technical and functional levels. Workmanship quality of A/E ensures that the designs are accurate and error free. Architectural quality concerns architects’ creativity, which has been discussed under ‘general mental ability’ (see H1.1).

An A/E who is from a large firm may exhibit greater task proficiency. This is because large firms have more financial and manpower resources and thus could give proper support to the project. If the project at hand is very urgent, it is also possible to mobilize all the staff to the project. Small firms are unable to do this and cannot be expected to expand quickly. Previous studies were not conclusive about the importance of the size of firms. Some found that large firms are advantageous (Veshosky 1994) while others found them to be disadvantageous (Hensey 1990; Poblador 1992). In the fieldwork, this attribute was further investigated. Besides size of firm, an A/E who has a manageable level of workload will be
able to give the client sufficient time and attention. Based on the above discussion, five attributes are identified under the criterion labeled as ‘task proficiency’:

- A/E produces designs which have technical quality (H3.1)
- A/E produces designs which have functional quality (H3.2)
- A/E produces designs which are accurate and error-free (H3.3)
- A/E is from a large firm (H3.4)
- A/E has a manageable level of workload (H3.5).

**JOB EXPERIENCE**

Studies have shown that more job experience leads to better job performance (McDaniel et al. 1988). Job experience may be measured in three ways; time-based, type-based and amount-based measures (Quinones et al. 1995). The time-based measure calls for measuring the number of years the A/E has practised in the construction industry. Secondly, the type-based measure indicates the need to evaluate whether the A/E has experience in projects which are similar to the project under consideration in terms of type and size. Amount-based measure of experience would mean the number of DB projects that the A/E has undertaken.

Based on the above discussion, three attributes are identified under the criterion labeled as ‘job experience’:

- A/E has practised in the construction industry for an adequate number of years (H4.1)
- A/E has experience in DB projects (H4.2).
- A/E has experience in projects which are similar to the DB project in terms of project type and size (H4.3)

**RESEARCH METHOD**

The literature review identified a list of attributes that A/E may need to possess to undertake CE. A fieldwork was mounted to determine which of these skills are held to be important by design-builders and A/E who practice in Singapore. Data were collected via postal questionnaire. The main part of the questionnaire comprised statements regarding attributes that A/E may need to possess in order to make them suitable for selection. These are the attributes identified in the preceding section. Respondents were asked to indicate the importance of the attributes on a five-point Likert scale, where 1 represented ‘very unimportant’, 3 for ‘good to have’ and 5 for ‘very important’. The survey package comprised a covering letter, the questionnaire, and a pre-stamped and self-addressed envelope. The respondents were given one month to reply to the survey.

In Singapore, there is no published list of design-builders. However, the Singapore Building and Construction Authority (BCA) has a system of registering contractors who wish to undertake public-sector construction projects. A research decision was made to send the survey package to the 208 BCA registered General Building and Civil Engineering
contractors who have paid-in capital (contributed capital from the owners) that are above US$1 million. This group was chosen because only relatively large contractors are expected to handle DB projects that usually need substantial amounts of resources. As the target population was contractors with DB experience, only survey responses from contractors who indicated that they had undertaken at least one DB project (Songer and Molenaar 1996) were subsequently considered for the study.

Questionnaires were also sent to randomly selected registered A/E who practice in Singapore. The sample size was set at 208 to match the sample size of contractors. This was to ensure that a meaningful statistical comparison could be made between responses from A/E and design-builders. This was based on the assumption that the response rates of A/E and design-builders would be comparable. In Singapore, there are 311, 274, and 115 registered architects, civil engineers and M&E engineers respectively. A sample size of 208 meant that approximately 29.7% of these A/E were to be surveyed. To ensure an even distribution, 29.7% of consultants from each discipline (93, 81 and 34 architects, civil engineers and M&E engineers respectively) were randomly selected.

RESULTS

Questionnaires were received from 51 (response rate= 25%) contractors with DB experience, and 55 (response rate= 26%) A/E, comprising 22, 27 and 6 architects, civil engineers and M&E engineers respectively. The response rates were within the acceptable range for surveys of this nature. The background of the respondents is shown in Table 1.

From Table 1, it can be seen that the respondents were holding senior positions in their firms, and had practised in the construction industry for a long period of time. These factors made the ratings dependable, and the views expressed by the respondents noteworthy.

Table 1: Characteristics of the respondents

<table>
<thead>
<tr>
<th>Sample</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Senior management and partners</td>
<td></td>
</tr>
<tr>
<td>Design-builders</td>
<td>32 respondents (63%)</td>
</tr>
<tr>
<td>A/E</td>
<td>45 respondents (82%)</td>
</tr>
<tr>
<td>Middle management and professionals</td>
<td></td>
</tr>
<tr>
<td>Design-builders</td>
<td>19 respondents (37%)</td>
</tr>
<tr>
<td>A/E</td>
<td>10 respondents (18%)</td>
</tr>
<tr>
<td>Average Years in Practice</td>
<td></td>
</tr>
<tr>
<td>Design-builders</td>
<td>17 years</td>
</tr>
<tr>
<td>Architects</td>
<td>16.3 years</td>
</tr>
<tr>
<td>Civil engineers</td>
<td>18.9 years</td>
</tr>
<tr>
<td>M&amp;E engineers</td>
<td>20.3 years</td>
</tr>
<tr>
<td>Experience in DB and CE</td>
<td></td>
</tr>
<tr>
<td>Design-builders</td>
<td>51 respondents (100%)</td>
</tr>
<tr>
<td>A/E</td>
<td>49 respondents (89%)</td>
</tr>
</tbody>
</table>
Mean importance ratings for all the attributes were calculated (see Table 2, column 2). Table 2 shows that the four most important attributes that A/E should possess to undertake DB and CE are:

- A/E has good knowledge of constructability (H2.2)
- A/E has good problem solving ability and project approach (H1.2)
- A/E has good knowledge of economical design (H2.1)
- A/E has good knowledge of design and regulations which are relevant to the DB project (H2.3).

Table 2: Statistical results of survey relating to attributes of A/E

<table>
<thead>
<tr>
<th>Criteria and Attributes</th>
<th>Mean (Design-Builder)</th>
<th>t test¹</th>
<th>Mean (A/E)</th>
<th>t test²</th>
</tr>
</thead>
<tbody>
<tr>
<td>General mental ability (H1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/E is creative and innovative (H1.1)</td>
<td>4.314</td>
<td>12.77</td>
<td>4.236</td>
<td>0.50</td>
</tr>
<tr>
<td>A/E has good problem solving ability and project approach (H1.2)</td>
<td>4.490</td>
<td>17.38</td>
<td>4.564</td>
<td>-0.51</td>
</tr>
<tr>
<td>Job knowledge (H2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/E has good knowledge of economical design (H2.1)</td>
<td>4.431</td>
<td>15.23</td>
<td>4.455</td>
<td>-0.17</td>
</tr>
<tr>
<td>A/E has good knowledge of constructability (H2.2)</td>
<td>4.608</td>
<td>17.25</td>
<td>4.400</td>
<td>1.58</td>
</tr>
<tr>
<td>A/E has good knowledge of design and regulations which are relevant to the DB project (H2.3)</td>
<td>4.431</td>
<td>15.23</td>
<td>4.109</td>
<td>2.02*</td>
</tr>
<tr>
<td>Task proficiency (H3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/E produces designs which have technical quality (H3.1)</td>
<td>4.059</td>
<td>12.32</td>
<td>3.946</td>
<td>0.87</td>
</tr>
<tr>
<td>A/E produces designs which have functional quality (H3.2)</td>
<td>4.196</td>
<td>15.08</td>
<td>4.218</td>
<td>-0.18</td>
</tr>
<tr>
<td>A/E produces designs which are accurate and error-free (H3.3)</td>
<td>4.294</td>
<td>13.18</td>
<td>4.109</td>
<td>1.28</td>
</tr>
<tr>
<td>A/E is from a large firm (H3.4)</td>
<td>3.000</td>
<td>0.00*</td>
<td>2.691</td>
<td>2.08*</td>
</tr>
<tr>
<td>A/E has a manageable level of workload (H3.5)</td>
<td>3.804</td>
<td>8.28</td>
<td>3.436</td>
<td>2.51*</td>
</tr>
<tr>
<td>Job experience (H4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/E has practised in the construction industry for an adequate number of years (H4.1)</td>
<td>3.431</td>
<td>4.23</td>
<td>3.564</td>
<td>-0.84</td>
</tr>
<tr>
<td>A/E has experience in DB projects (H4.2)</td>
<td>3.863</td>
<td>8.23</td>
<td>3.436</td>
<td>2.59*</td>
</tr>
<tr>
<td>A/E has experience in projects which are similar to the DB project in terms of project type and size (H4.3)</td>
<td>3.843</td>
<td>7.68</td>
<td>3.236</td>
<td>3.70*</td>
</tr>
</tbody>
</table>

Notes:  
- t-test¹: test of significance of the mean (of design-builders)  
- t-test²: test of difference between the means (between design-builders and A/E)  
- @ Attribute is not important at 95% confidence interval  
- *Design-builders and A/E did not rate in the same manner at 95% confidence interval

Statistical tests were carried out to check whether the population would consider the attributes to be important or otherwise. For each attribute, the null hypothesis that the attribute is unimportant and the alternative hypothesis that the attribute is important are set out. The Student’s t-test of the mean was used, and the cut-off t value is 1.6759 at 0.05 significant level. The results of the t-tests of the means are shown in Table 2 Column 3. Twelve of the 13 attributes have t values which are larger than $t_{(50, 0.05)} =1.6759$ at 95%
confidence interval. It is therefore concluded that when selecting A/E for DB project and CE, design-builders felt that it is important to choose those who have the 12 attributes identified. Contractors felt that it is not important to choose A/E who work in a large firm. This is evidenced by the t value of 0.00, which is smaller than \( t_{(50, 0.05)} = 1.6759 \).

To test whether design-builders and A/E regarded the attributes as having similar levels of importance, t-tests for equality of means of independent samples were carried out. The null hypothesis that the two population means are the same for each attribute and the alternative hypothesis that the two population means are not the same are set out. The level of significance for two-tailed test was set at 0.05, and the t value is approximately ±1.984. The results of the t-tests of the difference of the means are shown in Table 2 Column 5. Among the 13 attributes, design-builders and A/E did not attached similar levels of importance to five of them. The results are now discussed.

**DISCUSSION**

CE calls for contractors, major subcontractors and suppliers to be also involved during the design phase (Gunasekaran and Love 1998). DB is therefore well suited for CE, which calls for a multi-disciplinary team to contribute to the design of products, cooperate collectively, and the project participants must be able to take a holistic approach to the design and construction process to establish a creative, innovative and functional design that fulfils the clients’ requirements (Love and Gunasekaran 1997). It is important to engage the right A/E to ensure that CE can be carried out successfully.

The statistical tests showed that design-builders regarded both the attributes under the criterion of ‘general mental ability’ as important for A/E selection. To undertake CE, A/E need to be creative and innovative (H1.1). Among the 13 attributes, the second most important one is to choose A/E who have problem solving ability and a good project approach (H1.2). A/E with a good project approach help design-builders to win bids and ensure that upstream activities are reliably produced. A/E who are able to solve problems can ensure that the project will not be delayed.

The statistical test results showed that design-builders and A/E all regarded the three attributes under the ‘job knowledge’ criterion as important for A/E selection. It is important to choose A/E who have knowledge of economical design (H2.1) because economical designs enable design-builders to earn higher profits. It is also important to choose A/E who have knowledge of constructability (H2.2) so that design-builders can complete the construction work faster. The survey results also showed that it is important to choose A/E who have good knowledge of design and regulations which are relevant to the DB project (H2.3) because the drawings are likely to be approved faster by the owners and authorities. These three attributes, which relate to the upstream activity of design, are also three of the four most important attributes in A/E selection. If A/E have the job knowledge to produce a good design through CE, downstream problems can be minimized.

A/E accorded lower level of importance to the need to have good knowledge of design and regulations which are relevant to the DB project. This may be because A/E felt that job knowledge can be learnt as the project progresses.
It is important to choose A/E who can produce designs which have technical quality (H3.1) so as to meet all the standards in the relevant codes. It is also important to choose those who can produce designs which have functional quality (H3.2), so as to meet the needs of the owners. A/E should be able to produce designs which are accurate and error-free (H3.3). This is an important CE concept, in order to avoid unnecessary delays or incurring extra costs for reworks arising from drawings which contain errors.

Attribute H3.4 “A/E is from a large firm” is regarded as unimportant by design-builders and A/E. It is not necessary for A/E to be from large design firms, as small consulting firms are also able to handle projects well. If these small firms needed extra staff, they could expand relatively easily by recruiting more professionals. This finding shows that even though large firms may have sufficient resources, and an adequate number of technical and professional staff, these do not help them in being selected because they may have higher overheads, leading to higher fees, and thus lower competitiveness. Large firms may also have more and bigger projects. Thus, the partners may not be able to give enough personal attention to each of the projects. In addition, large firms may have more rules and procedures, which may make them more bureaucratic, less agile and thus less able to respond quickly. When organizations are too large, they become less effective than those whose sizes are appropriate or too small due to the additional co-ordination which will be required (Campion et al. 1996).

The survey showed that design-builders would select A/E who have a manageable level of workload (H3.5). This is to ensure that designs and drawings can be completed speedily, CE can be carried out, and construction work will not be delayed. It is interesting to note that A/E accorded significantly lower level of importance to this attribute. They may have felt that in a tight labor market situation, there are many jobs but insufficient qualified manpower to handle these jobs. They may not have a manageable level of workload, but so long as they could earn more fees, this would be advantageous to them.

Design-builders and A/E felt that it is important for A/E to have practised in the construction industry for a relatively long period of time (H4.1). Design-builders felt that it is important to choose A/E who have experience in DB projects (H4.2) and in projects which are similar to the project under consideration in terms of type and size (H4.3). On the other hand, A/E accorded lower level of importance to these two attributes. A/E may have felt that DB is relatively new in Singapore and it is therefore not important that they should have experience in DB projects. In addition, a competent A/E has the ability to tackle a wide range of projects, based on a broader interpretation of the concept of ‘job experience’.

LIMITATIONS

One limitation of this study is the relatively low response rates. Therefore, the data gathered may not be truly representative of various groups of people operating in the construction industry. Another limitation is that the depth of respondents’ experience in DB and CE was not the same because respondents have undertaken different numbers of projects and these projects are of different sizes and complexity. A survey of this nature suffers from the possibility that the respondents did not really think through the questions before answering,
and there is the possibility of bias. There was also a lack of control over who actually completed them. There may also be different interpretations of the Likert scale.

The limitations identified above are not expected to nullify the findings of this study. This is because as DB and CE are relatively new in Singapore, the 51 respondents could represent a large and significant percentage of design-builders in Singapore, notwithstanding the relatively low response rate. For A/E, a large percentage of them had been surveyed too. In order to lessen the problem of bias, not thinking through before replying and having incompetent personnel reply to the questionnaires, the survey forms were sent to managing directors and senior partners of the firms. The problem of different interpretations of the Likert scale was lessened by assigning a description to each point on the scale.

CONCLUSIONS

The Theory of Job Performance specifies four variables which affect job performance: ‘general mental ability’, ‘job knowledge’, ‘task proficiency’, and ‘job experience’. This theory and the four variables are generally supported in this study, as seen from the survey results and statistical tests, which are summarized in Table 2. The specific attributes required include: being creative and innovative; having good problem solving ability and project approach; having good job knowledge; being able to produce accurate designs which have technical and functional quality; having manageable levels of workload; and having the necessary job experience.

In conclusion, the results showed that design-builders’ way of selecting A/E to undertake DB projects and CE supports the Theory of Job Performance proposed in the theoretical framework. The Theory of Task Performance, derived from the literature pertaining to personnel psychology, has been formulated for employee selection (which is a contract of service). This study shows that it is also equally applicable to consultant selection (contract for services), even though consultants are not direct employees of the selectors.

The practical implication of this research is that in order to be engaged to provide CE services, A/E should concentrate on the more important attributes identified in this paper and go about acquiring the necessary attributes. If A/E already possess these attributes, this study suggests the more important ones that they should hone in on. Attributes relating to general mental ability may be acquired by ‘thinking outside the box’. Job knowledge is acquired by learning in depth how tasks are to be performed (declarative knowledge) and having hands-on experience to the point that performing the task becomes relatively automatic (procedural knowledge) (Kanfer and Ackerman 1989). A/E may acquire attributes relating to task proficiency by undertaking their work with skill and competence. Unfortunately, job experience related attributes can only be acquired through the passage of time and the exposure to many types of projects. A/E firms may wish to consider taking on a variety of project assignments, instead of concentrating in a narrow sub-market.

A/E need to change their mindsets on several issues. Specifically, A/E should note that design-builders place far more importance on good knowledge of design and regulations which are relevant to the DB project. Consulting firms should also endeavor to expose their A/E to DB projects and to different types of projects. Design-builders also sent a strong
message to A/E- that they want them to manage their workloads, as A/E who are overloaded with projects would not be selected.

For new contractors who are just starting to embark on DB and CE, the usefulness of this study is that they could use the results to evaluate and select A/E. They should not merely select based on word of mouth, or the A/E’s reputation, or the size of the A/E’s firm. There are several ways to obtain data to evaluate the A/E. For attributes relating to general mental ability, job knowledge and quality of design, the evaluation should be based on A/E’s past projects, preferably those that were undertaken together with the selector’s firm. The selector’s project manager could be asked to evaluate the A/E. Alternatively, A/E could be asked to submit three past projects, and the selector could then interview the project managers. To evaluate A/E’s job experience, selectors could ask A/E to provide the necessary information as listed in Table 2. It is acknowledge that there may be difficulty in evaluating whether A/E have a manageable level of workload. One measure of workload that selectors may consider is the ratio of the number of projects to the number of professional staff.

REFERENCES


procuring construction projects.” *International J. Project Mgmt.*, 16(6), 375-383.
Pain, J. and Bennett, J. (1988). “JCT with contractor's design form of contract: a study in
design/build fast-track construction projects.” *J. Constr. Engrg. and Mgmt.*, ASCE,
127(1), 1-17.
experience and job performance: a conceptual and meta-analytic review.” *Personnel
Psychology*, 48(4), 887-910.
Ree, M.J. and Earles, J.A. (1993). “‘g’ is to psychology what carbon is to chemistry: a reply
to Sternberg and Wagner, McClelland, and Calfee.” *Current Directions in Psychological
Science*, 2(1), 11-12.
knowledge in complex training performance.” *J. Applied Psychology*, 80(6), 721-730.
ability on job knowledge, work sample performance, and supervisory ratings of job
owner attitudes.” *J. Mgmt. Engrg.*, ASCE, 12(6), 47-53.
Engrg.*, ASCE, 10(5), 41-47.
DEVELOPING DECISION AGENT FRAMES IN PROJECT DEFINITION: RESEARCH IN SHARED UNDERSTANDING

Michael Whelton\textsuperscript{1} and Glenn Ballard\textsuperscript{2}

ABSTRACT
Product development has been transformed from a traditional sequential development process towards a more concurrent and collaborative process, yielding shorter lead times, reduced project costs, improved product quality, and greater process efficiency and effectiveness. The organizational design and creation of cross-functional teams to execute projects has been recognized by other industry sectors, e.g., the manufacturing industry, as a positive value generating mechanism for project delivery. Similarly in construction, generating understanding in the use of teams to develop successful projects is required. In this paper, particular focus is given to group work activity during project definition, understood as the phase in which exploration of alternatives creates innovative problem and solution definitions that allows generation of greater customer value. This paper explores the development and communication of group problem framing by multiple decision agents. A set of research propositions are proposed to examine group dialogue and shared understanding. Greater support and understanding of cognitive processes used by project stakeholders in group tasks is essential, if cross-functional teamwork is to be productive within the project definition process.

KEY WORDS
Cross-functional teams, dialogue, frames, language/action, project definition.

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INTRODUCTION

Barrett and Stanley (1999) and Kamara and Anumba (2001), speaking about the UK construction industry, describe problems observed with respect to communication of information and implementation of appropriate (project definition) decision processes within teams. Disorganized behavior within design teams may result from inadequacies in process structure or framework. Project teams use a wide range of paradigms and perspectives for decision making in the pre-design phases of capital projects (Woodhead 1999). Design and construction organizations need a better understanding of these perspectives and the dynamic and changing influences impacting them. Multiple perspectives create complex frames of reality and add to poor decision-making quality without the support of a common decision channel and language. It is vitally important to develop multiple perspectives or frames to understand how project decisions are made by organizations. Woodhead and Male (2000) conclude that “gaining an understanding of the role played by paradigms and perspectives is a necessary step towards rethinking the pre-project stage, what we do in the process and why. This understanding empowers decision makers as they can then avoid having their decisions conditioned by external forces and make more informed choices. To achieve an improved capital proposal stage, design and construction organizations need a better understanding of the organizational and strategic values that direct the core business and its building programs”.

The nature of the decisions to be made adds another level of complexity. Where decision problems are more complex and cannot be easily defined by the decision makers, rational and systematic process methods are more difficult to apply. Such problems include solving a set of interlocking issues and constraints by multiple stakeholders. Complex systems may exhibit or pose ill-structured problems, which groups or teams come together to solve, often finding themselves operating within complex information3 and decision ecologies. Rasmussen (1997) considers this environment an adaptive socio-technical system.

The authors have advanced situational studies (Whelton and Ballard 2002) to argue that project definition performance is impacted by a complex network of decision action by stakeholders over the course of a project definition process. Exploratory case studies illuminate the complexity of formulating project definition problems and generating solutions. The empirical studies support the idea of limited or bounded rationality (Simon 1969) in organizational decision practice. Illustration of complex decision ecologies4 suggests that greater transparency of decision networks is required in order for cross-functional project definition teams to generate maximum client value at the project definition phase. Facilitating transparency of stakeholder interests is a notable feature of the case materials. March (1994) supports this theory of decision making in real world situations. He suggests that not all alternatives are known, that not all consequences are considered, and that not all preferences are evoked at the same time. Bilello (1993) develops multiple frames

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3 Davenport (1997) also proposes the ecology metaphor to describe holistic management of information within its environment, and the associated system components.

4 March (1999) describes an “ecological” view of decision making which “considers how the structure of relationships among individual units interact with the behavior of these units to produce systematic properties not easily attributable to individual behavior alone”.
for understanding how different organizations structure a problem for decision-making purposes. Decision agents may choose the explanations which are most plausible to them. Maintaining a broad worldview of the problem definition can aid in resolving the complex situation. The inability of project teams to establish explicit multi-dimensional decision models for decision agents is notable.

The paper addresses the lack of knowledge in understanding group complexity, the efficiency of group work, and the effectiveness of collective group decision making. The work is centered about project definition practice, a project delivery phase regarded as most influential in terms of client and stakeholder value generation. In this paper the term “project definition” will be used to encompass all project activity prior to design development. The product of the project definition process is a formulation of the project’s problem definition and solution specification to fulfill the client’s purpose and project requirements. Sufficient testing of client purpose, project criteria and design concepts to verify and validate the success of the project is the objective of project definition.

In particular, this paper is proposing a framework for analyzing the management of group dialogue in project definition activity. The paper reports on a research strategy that bases its assumptions on existing project definition research and exploratory case work carried out by the authors. The main body of the paper reports on a framework for developing group shared understanding. A conceptual model is first proposed to identify group work. Understanding decision agent frames by which problem formulation and solution generation are developed leads to improved transparency of the group process. The research focuses on the decision agent frame as the level of analysis. The importance of frames is discussed and a model to identify frames within task oriented group dialogue is proposed. The need to understand groups as complex systems is advocated. Group frameworks can support communication and development of “shared understanding” in project definition processes. Therefore, facilitating the management of frame development is advocated. The research adopts the language/action perspective (Winograd and Flores 1986) to understand how groups act through language, and learn through dialogue.

Central to understanding team learning in project definition is the appropriate facilitation of reflection processes. Testing the degree of shared understanding can be applied through the facilitation of reflection points within the process, and through the use of intervention questions. How the dialogue process is facilitated and directed is a central component towards developing shared understanding. The research advances Argyris’s (1999) theory of organizational learning, Schon’s (1983) notion of reflection by groups, and Rittel’s (1972) process of argumentation for solving design and planning problems within a learning process model. Organizational learning is the “intentional use of learning processes at the individual, group and systems level to continuously transform the organization in a direction that is increasingly satisfying to its stakeholders” (Dixon 1999). Project definition activity can be considered such a learning process.

Finally a case example is illustrated to identify group dialogue and resulting actions set by the group. This paper presents a set of experimental research propositions to investigate the complexity of group processes centered about the language/action perspective. Central to this research approach is the focus on conversation networks. Creating a common language-action framework for project definition activity supports the creation of shared understanding. Experimentation with group dialogue can lead to management insights that
support the overall facilitation of shared understanding and develop appropriate transparency in the project definition process. Supporting group learning and collective knowledge creation is critical for effective value generation to occur in project definition activity.

**PROJECT DEFINITION AND GROUP PROCESS PERFORMANCE**

Traditional project organizations are formed through fee-based cost structures. Many parties coming together on projects are formed from different disciplines and often from different organizations. These relationships may only exist as casual working relationships (Liston et al. 2001). The exploratory case studies (Whelton and Ballard 2002) reveal a lack of quality in the design of the group process. Table 1 summarizes the primary organizational factors that impact the successful creation and transfer of project definition knowledge in project definition activity. These quality issues are consistent with those reported in project definition related research literature (Kamara and Anumba 2001, Barrett and Stanley 1999, Koskela et al. 2002). The identification of process quality inefficiencies leads to the question in what ways do project based organizations think as groups during the process of project definition.

**Table 1: Process Inefficiencies**

<table>
<thead>
<tr>
<th>Management - Quality Category</th>
<th>Process Inefficiency Instance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Management of the definition process</strong></td>
<td>Lack of shared process model</td>
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<tr>
<td></td>
<td>Undefined roles and responsibilities</td>
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<tr>
<td></td>
<td>Poor constraints analysis</td>
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<td></td>
<td>Unrealistic budget and schedules</td>
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<tr>
<td></td>
<td>Poor use of phases and gates</td>
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<tr>
<td></td>
<td>Insufficient time for project definition</td>
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<tr>
<td></td>
<td>Poor change management</td>
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<tr>
<td></td>
<td>Limited resource allocation to project definition processes</td>
</tr>
<tr>
<td></td>
<td>Lack of formal review and learning processes</td>
</tr>
<tr>
<td><strong>Stakeholder involvement &amp; communications</strong></td>
<td>Lack of ‘voice’ of the user group(s)</td>
</tr>
<tr>
<td></td>
<td>Inadequate stakeholder involvement and participation</td>
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<tr>
<td></td>
<td>Poor group dynamics</td>
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<td></td>
<td>Misunderstanding of client organization and culture</td>
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<tr>
<td></td>
<td>Lack of client education of process</td>
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<tr>
<td><strong>Collection and documentation of information</strong></td>
<td>Poor traceability of requirements</td>
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<tr>
<td></td>
<td>Lack of/poor visualization of needs, criteria and concepts</td>
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<tr>
<td></td>
<td>Ill structured project memory &amp; Poor transfer of information</td>
</tr>
<tr>
<td><strong>Processing of information</strong></td>
<td>Poor programming of needs</td>
</tr>
<tr>
<td></td>
<td>Lack of poor assessment of clients needs and project life cycle needs - (Trial and error processing methods)</td>
</tr>
<tr>
<td><strong>Decision-making</strong></td>
<td>Subjective negotiations in conflict resolution</td>
</tr>
<tr>
<td></td>
<td>Lack of solution expansion and exploration</td>
</tr>
<tr>
<td></td>
<td>Lack of group decision support tools</td>
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</tbody>
</table>

The development of systematic support tools, such as QFD employed in Kamara and Anumba’s Client Requirements Processing Model (CRPM), show promise of improving clarity and rigor of project definition processes. While these support processes and tools
provide structure and transparency within project definition, group problem framing practices require further attention, as research (Green 1996) has identified organizational complexity associated with varying organizational structures and decision practices.

**SHARED UNDERSTANDING AMONG GROUPS**

In recent years, the view of design as an essentially individual creative activity has come under increasing question (Scrivener et al. 2000). Instead, for a variety of reasons, design is being viewed, studied and developed as a collective, collaborative even community process. Multiple phrases for example: collaborative, cooperative, concurrent, user-centered, participatory, socio-technical and community design denote design development that include group processes”.

Teamwork performance of a concurrent engineering organization is largely controlled by the design of “concurrent product development teams”. Prasad (1998) identifies four key elements of decentralized cooperation, namely, convergence and collaborative thinking, empowerment, team recognition, and deep common understanding. While not within the direct focus of this paper, it is important to identify other group and team aspects which include: verbal and non verbal communication, listening and feedback, group norms, roles, cohesiveness, groupthink, leadership, group development, group diversity, creativity and problem solving, decision practices, conflict management, media use and computer support.

Groups are complex, adaptive, dynamic, and act as bounded sets of patterned relations among members, tasks and tools. The acknowledgment that design is a highly social process and that there is high dependency on teams to successfully develop the design process, also reveals the importance of group dynamics in terms of communications and collaborative decision-making. Within teams, there is normally some degree of shared understanding of the goals and objectives required in achieving a valued project. However, shared understanding of objectives is never perfect, and specialization implies unequal distribution of know-how regarding means. Team actors may frame the problem within constructs of their own expertise or experience (Beach 1997). Shared understanding is a broad construct which describes mutual expectations by group members and the extent to which teams are able to establish a common platform for their task. It may be considered a cognitive variable or a group mental model (Cohen et al. 1999). Establishing shared understanding requires developing group language, roles, goals and priorities, group purpose and ways of getting work done. How well member differences are identified and acknowledged, determines the level of shared understanding.

Hill et al. (2001) identify team-based design activity as the generation of design knowledge which is codified and reflected on in an ongoing process between the various stakeholders. Learning occurs through reflection and re-evaluation of the project knowledge generated. Shared understanding emerges when the team establishes a common frame of reference. This research assumes that: 1) developing shared understanding in project definition groups improves task effectiveness; and 2) understanding the profile of the decision agent and its decision frame improves shared understanding.
CONCEPTUAL GROUP WORK MODEL

Figure 1 illustrates a conceptual model detailing the use of problem formulation tools and methods. The process operates within private individual models and shared group models.

DEcision Agent Private Model

Discourse cycles develop about the problem formulation and solution generation through the use of methods and tools appropriate for the problem context. The meta-process that defines the appropriate selection and use of the tools is dependent on the problem context, the available resources and knowledge skills associated with the group. Such tools include economic and business models, planning, architectural and engineering models, and visualization models as well as data gathering and information management tools. Methods that structure the problem within the domain knowledge of the agent or sub-group are included in this category.

Meta-Planning Process Model

The meta-process chosen to communicate shared understanding is central to this investigation. Formal group processes help: structuring of group tasks, analysis of the problem context, create ideas toward solution generation and create agreement among the decision agents. How the problem is structured determines the direction of the solution formulation. Sunwolf and Seibold (1999) detail group procedures that support the above situations.

Group Shared Meaning Model

Developing or working project definition issues are shared with the appropriate group agents in order to build and maintain shared understanding about the problem context. Again the meta-process that fulfills the development of shared understanding considers the appropriate use of methods and tools. In this process understanding and respect of the other project
agent’s needs become apparent. This collective process establishes project issues that verify or falsify the process direction. Appropriate time and resource allocation within the process is necessary to support dialog for reflection and argumentation, which may result in subsequent learning and appropriate implementation of change.

COMMUNICATING FRAMES WITHIN THE GROUP PROCESS

The role of communication is complex, especially as symbolic behavior between people in the form of language and nonverbal behavior, and is the glue that holds effective small groups and teams together. Communication is the recognition of certain behavior that is meaningful to one or more participants. Meaning-centered activity is the aim of team communication. Meaning is usually based on a symbolic interpretation of another’s communication and is contextually based. Communication allows the team to apply meaning to situational conditions through simultaneous transmission and receiving of behavioral events (Harris 2002).

In project definition, developing the problem and solution can be seen as co-evolving acts. While Kamara and Anumba (2001) propose solution neutral specifications through requirements processing, full testing of purpose and criteria may only be validated through concept generation and reflection. As designers are primarily solution focused (Cross 2001), testing of client purpose and design criteria can only be fully verified and validated through the development of design concepts, particularly when client organizations are complex and multi-faceted. Rittel (1984) suggests investigating “designing as an argumentative process; where to begin to develop settings, rules and procedures for the open-ending of such an argumentative process; how to understand design as a counter-play of raising issues and dealing with them, which in turn raises new issues”. As the case studies suggest, recognition of distributed expertise and ignorance throughout a set of project participants is necessary for developing alignment of project definition.

Generating a communication language to promote the co-evolution of problem/solutions is important. Achieving higher levels of stakeholder commitments may lead toward developing a greater sense of shared understanding of the project definition, which in turn supports effective collective action.

STAKEHOLDER PROBLEM FRAMING

In order to develop a sense of how teams develop shared understanding of project definition problems and solutions, it is necessary to understand the “frames” by which the various team members structure the collaborative decision making process.

Framing involves embedding observed events in a context that gives them meaning. Beach (1997) defines a frame as a “mental construct consisting of elements, and the relationships between them, that are associated with a situation of interest to a decision maker. The elements are salient to current or past events. The relationships define the expected interactions among the elements”. Should the frame not represent a valid representation of the situation, the frame is revised through replacement or reinterpretation of the various elements and relationships.

Frame analysis is the study of the ways in which practitioners frame problems and roles, and it can aid in allowing stakeholders to become more aware of and criticize their roles
Explication of stakeholder frames requires consideration in the group decision process. This issue resonates with Bilello’s (1993) work on developing multiple perspectives in product development processes. The different frames of decision making vary for the decision agents involved. Schon’s notion of reflection allows a group to surface and criticize the tacit understandings that have grown up around a repetitive experience of the group, and make new sense of situations of uncertainty or uniqueness. Stumpf and McDonald (2002) support reflection in action in their analyses of frames to support experiential learning in groups.

Problem frames involve the problem and the problem solver relationship and cannot be defined solely in terms of the problem at hand. Framing depends on available knowledge of the problem domain, existing problem solving techniques and problem solvers’ basic cognitive capacities. Project definition outcomes are therefore determined by the acquisition of appropriate domain knowledge, the correct implementation of problem solving methods, and the cognitive capacity of individual decision agents and of the group. Based on this section the following assumptions are considered valid based on previous research: (1) project definition groups are comprised of complex decision agents that utilize multiple paradigms and perspectives in their decision processes and (2) the appropriate availability and performance of group domain knowledge, problem solving methods and cognitive capabilities determine project definition outcomes.

Figure 2 illustrates a group action model that seeks to model group dialogue in experimental group settings. Emphasis is placed on participative communication and reflective action by project groups. Mapping conversation types with generic group tasks as defined by McGrath (1984) allows experimentation with quality of task completion and effectiveness. Figure 2 displays some exploratory questions proposed by Buenano that exemplify processes for reflective conversation.

![Figure 2: Conceptual Group Action Model](image)

Woodhead (1999) provides useful role definitions for project stakeholder involvement in project definition activity. Agent roles distinct or overlapping include: decision approvers,
stakeholders that approve the project definition for development; decision takers, stakeholders that take or approve a project decision to move to the next phase; decision shapers, stakeholders who develop and shape the project definition (e.g., the cross-functional team), prior to submitting it to decision takers; and finally decision influencers (e.g., product users), stakeholders formal or informal who influence the project definition shape. Such taxonomy of role definitions provides an initial structure upon which to further establish agent profiles, and related decision practices which can improve group shared understanding.

Structuring of frames will depend on the belief and value systems held by team members. Mutual understanding of individual frames aids the process of alignment into a shared collective frame. Much complexity exists due to the misalignment of problem framing among project definition participants. How do teams reframe the problem once the original frame has been iterated on and deemed incomplete? How information is communicated, directed, and processed by those responsible for initial and final framing of project definition decisions becomes a core issue for understanding.

The following assumptions are made regarding project definition framing by groups: (1) systematic project definition methods require supporting processes of group argumentation and reflection to explicate problem formulation and solution generation issues; (2) facilitating frame – reflection cycles by multiple decision agents provides explication and clarity of project definition issues; and (3) establishing a process “learning agent or group facilitator” with explicit dissent roles, challenges the project definition problem formulation and solutions.

**Utilizing the Language/Action Perspective**

A central approach in understanding cooperative group work is the important topic of language/action. Within the language action perspective, people are considered to act through language. Organizations are conceived as networks of directives and commissives. Directives include orders, requests, consultations, and offers. Commissives include promises, acceptance and rejections. Conversations for action form the central fabric for cooperative work (Winograd and Flores 1987). Kensing and Winograd (1991) view cooperative work as being coordinated by the performance of language acts through which parties become mutually committed to the performance of future actions.

A conversation is a collection of speech acts by participants who are mutually concerned with the completion of particular “conditions of satisfaction”. Additional kinds of conversation support action; namely, conversation for clarification, conversation for possibilities, and conversation for orientation (Winograd 1986). Explication of these conversation types within the larger network of conversation can help understand the roles that language acts play in a variety of conversation, and to match expectation to those roles.

Project definition activity can occur within what Carroll (2001) defines as scenario-based design. Scenario-based learning focuses on human centered issues, towards which the final product is ultimately directed. Working with scenario descriptions of the problem context evokes reflection in the context of project definition activity. Scenario descriptions may occur at the strategic, conceptual, or detail operations system level as defined by the decision agent in question.
The following communication instance is developed to emphasize how social processes occur and how the use of language in a group setting evolves. The meeting in which this design conversation occurred had advertised a very different agenda which was focused on assessing the completion of information documents. The project manager queried the condition of the facilities in relation to Accessibility Code (American Disabilities Act – ADA) compliance. The responses triggered an unforeseen set of reactive design planning processes. The illustrated conversation in Figure 3 can be further analyzed in terms of team actions. The dialogue begins with problem orientation. Issues are clarified and searches for possible solutions occur. Process transparency is clear in this instance of group dialogue. Categorizing the actions by conversation type can help the facilitator better direct the group dialogue process.

**Figure 3: Project Definition Scenario Group Dialogue**

**FUTURE EXPERIMENTAL RESEARCH**

Structuring appropriate facilitation of conversation types may reveal a richer understanding of the project definition issue. Investigating the degree of conversation quality established about an issue can aid in improving overall group process quality. Getting the group focused on issue-based argumentation and reflection can reveal project definition issues more effectively than would an information processing perspective, as was observed in this case instance. The following propositions are proposed for further experimental analysis:

** Proposition 1:** As communicative acts form the basis for group action, dialogue systems serve as appropriate frameworks for task analysis,

** Proposition 2:** Speech act tools allow the process learning agent to analyze group coherence, and assess the degree of shared understanding in project definition issues.
Proposition 3: Decision agent value systems are explicated in a dialogue system utilizing iterative cycles of action, reflection and learning.

Proposition 4: Group mental mapping tools and methods explicate decision agent problem frames and improve group process transparency.

Proposition 5: Group learning is influenced by the quality of group dialogue management.

CONCLUSIONS

Project definition can be defined in many ways and has different meaning to each project stakeholder. It may be meant as a formal process or perceived as a social activity. Project definition can be ill-structured, with competing decision views or frames. To understand the group cognition aspects of project definition activity, it is necessary to explicate these influencing paradigms and perspectives used by project stakeholders and their organizational units. Only through the establishment of such perspectives can an understanding be gained on how to better generate and share knowledge within the project definition group. Linking the cognitive processes of the project stakeholders to tangible decisions and project definition artifacts is a common feature in understanding the process.

This research seeks to improve clarity of group action and to develop appropriate transparency in project definition practice. This paper has identified process inefficiency and complexity associated with group work. The importance of developing shared understanding among group participants has been highlighted. We have proposed a set of assumptions and propositions for understanding the effectiveness of group tasks in project definition activity. Our future research will use a language-action framework to study group dialogue and the facilitation of dialogue, using both quantitative and qualitative metrics. Understanding the group adaptation process as the dialogue evolves should help reveal how to actively direct that process and improve project definition.

REFERENCES


Harris, T.E. (2002). Small Group and Team Communication. 2nd edition, Allyn and Bacon, Boston, MA.


INDUSTRY PERSPECTIVES ON THE IMPACT OF IT AND E-COMMERCE

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ABSTRACT

In recent years several new IT-based technologies such as e-commerce have been developed, which if applied to the construction industry can prove beneficial. Before the implementation of new technologies and applications, it is essential to identify the factors that the industry perceives as being the enablers and barriers to the uptake of these applications for greater effectiveness. This paper presents the results of a survey undertaken to establish the views of industry practitioners on the uptake of IT (and e-commerce in particular) within the UK construction sector. The survey explored attitudes, current usage, barriers and enablers amongst other things. The findings of the survey are briefly discussed and outline ideas for more effective deployment of IT and e-commerce in construction organisations presented. The paper also tries to outline some future prospects for using e-commerce in the UK construction industry, based on responses to the survey.

KEYWORDS

Information technology, e-commerce, construction innovation, UK construction, e-commerce barriers and enablers

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INTRODUCTION

It has been well documented that the construction industry is characterised as being both fragmented (Anumba and Evbuomwan 1999; Egan 1998; Lottaz et al. 2000) and information-intensive (Thomas et al. 2001). A considerable degree of information flows between disciplines including client, architect, structural designer, quantity surveyor, services engineer, fabricator, subcontractors, contractor and material suppliers. A construction project is a team effort, which involves several inter-organisational activities, dialogues and data flows, making it a highly complex process (Egan 1998). Currently, the information flow in the construction industry is mostly paper-based and hence slow. Also there is the likelihood that there will be increasing amount of communication blockages as the projects grow larger and more complex (Thomas et al. 2001). Conventional paper-based methods of communicating information are grossly inadequate particularly in collaborative/concurrent engineering settings where the project team members may be geographically distributed. It is therefore very important for construction project teams to look at alternative and more effective ways of communicating through the project lifecycle. Construction projects can incur considerable savings in terms of time and money by adopting dynamic methods of information exchange and communication facilitated by IT and e-commerce tools. The exponential growth of the Internet and the growing use of IT have accelerated the pace of change, and demand more flexible and adaptive organizations (Malone and Crowston 1991). Construction organisations that decide to enhance their business processes using IT and the Internet should recognise that adopting such ‘innovative’ methods will facilitate in integration of the entire management process for construction projects. The flow of information in such a system will be electronic and hence interactive. It will make use of the Internet as a ‘medium’ for data storage, data transfer, communication, conferencing, dialogue and decision-making and acquiring information. All these tasks would be carried out in a monitored and secure environment.

With developments in IT, the construction industry is adopting new and innovative tools to overcome the current inefficiencies in its project processes; these are mainly through facilities for exchanging and organizing project information (Lottaz et. al 2000). A survey of the UK construction industry, undertaken by the Construction Products Association (CPA 2000), predicted that by 2005, 50% of the industry’s business activity would be undertaken using e-commerce. However, another survey carried out a year later by the same organisation (CPA 2001) indicated a considerable reduction in these projected figures to 22%. The construction industry stepping back from the initial ‘dotcom fever’ was seen as the main reason of this change. This paper presents selected results from a 2001 survey on Information Technology and E-commerce in Construction that was carried out to establish the current usage of IT and e-commerce in the UK construction sector. This survey has been carried out as a part of a broader research project on ‘Business Process Implications of E-commerce in Construction’ at Loughborough University. The primary objectives of the survey were:

• To establish the readiness of UK construction industry to adopt IT and, in particular, e-commerce technologies and;
To identify the barriers and enablers to the implementation of these technologies in the day-to-day construction processes.

The paper gives background information about the survey questionnaire and objectively analyses the results using illustrative charts and statistical data as appropriate. Finally, the paper discusses the future prospects for using e-commerce in UK construction, based on the survey results.

SURVEY BACKGROUND AND METHODOLOGY

Several surveys have been conducted in the past couple of years to determine the impact of IT in the construction industry worldwide (Rivard 2000). In the UK surveys have been conducted to gauge IT usage within the construction sector by DETR in 1999 and by the CPA in 2000 and 2001. The data used in the DETR survey is already three years old, while the CPA survey concentrated on e-commerce transactions within the construction supply chain, and particularly with respect to construction product suppliers. The survey conducted by the authors mainly focuses on the uptake of e-commerce and IT within the construction industry and identifies the main barriers and enablers. It is vital that the barriers, enablers and the potential of using technologies such as e-commerce are identified, examined and analysed in order to make recommendations for an effective uptake of these technologies within the construction industry. The findings of this survey will be used as one of the sources to formulate an effective strategy for development and uptake of new e-commerce applications in the construction sector. In order to benefit fully from such technologies will require changes to the existing business processes (Howard and Andresen 2000). This is one of the key objectives of the research project that looks into reengineering the current construction business processes with particular focus on suppliers and end users.

The survey was carried out in the first half of 2001. The questionnaire occupied four sides of A4 paper. Paper copies of the survey questionnaire were distributed by post to a random sample of 145 construction organisations encompassing various construction disciplines including architects, engineers, contractors, manufacturers and suppliers within the UK. Each respondent was given the opportunity to respond anonymously, however, a high percentage of all the respondents provided contact details to receive a copy of the survey results. The findings presented here are based on an overall response rate of 22%.

SURVEY ANALYSIS AND RESULTS

Selected results from the survey are presented in this paper and include computer usage (hardware and software), communication networks (inter and intra-disciplinary levels), information technology, and e-commerce technology within the UK construction sector.

COMPUTER USAGE

This section considers the level of computer usage and includes the use of different types of operating systems, office software applications and specialist applications performing specific business operations. The survey results indicate that the type of operating system
used varies from company to company, with the Microsoft Windows being the most commonly used.

Effective communication is key to the success of any construction project. It has been well documented that a wide array of communication problems, ranging from delays to distortion of messages, can impose strains on overall construction project management and project performance. The prohibitive costs of making long distance calls, facsimile transmission etc, have made the project management community in construction look for more viable alternatives (Alshawi and Ingirige 2002). The survey results have shown that the use of e-mail as a mode of communication is common and almost all companies surveyed use e-mail. Continuing the trend of dominant usage of Microsoft applications, it is seen that MS Outlook (73%) is the most commonly used e-mail application.

There are several specialist project management software applications available in the market and the survey results show that a high percentage of responding companies use project management software applications to manage projects. 53% of the respondents use MS Project as a project-planning tool while 27% used Primavera (www.primavera.com). Other planning tools PowerProject (www.astadev.de) and SureTrak (www.primavera.com/products/sure) are also used.

The survey also investigated the types of database systems used in the industry and the results suggest that the use of these systems is relatively common amongst participant construction organisations. The use of MS Access (65%) is higher than that of other database systems such as Lotus Approach (5%), dBase (5%) and SQL (15%). The remaining 10% use other database programs (e.g. Oracle).

The main output of any architectural and engineering firms is drawings and these drawings are now mostly generated using computers (Rivard 2000). The survey results indicate that CAD (Computer Aided Drafting) packages are widely used throughout the industry. While 100% of the architects use CAD packages for design drawings, the average percentage of CAD usage in the industry (including manufacturers and contractors) is 87%. CAD in this context refers to 2D(two-dimensional) CAD drawings.

COMMUNICATION NETWORKS FOR CONSTRUCTION

The efficiency with which information is communicated between different project partners of a construction project will depend on the communication systems that are being used by each individual organisation involved in the project. The survey tried to establish the percentage usage of different communication media including mobile phones, personal email, pagers and Internet, amongst office and on-site construction staff. Amongst construction companies, over 65% of office staff are connected to the Internet and over 85% have access to e-mail (Figure 1). In contrast, only 40% of site staff has e-mail access. The use of mobile phones is twice as high for on-site staff (approx. 60%), as for office staff. This suggests that there is a high percentage of use of communication media within UK construction supply chain.
In recent years an increasing number of companies make use of the Internet to advertise and market their products and services (Ruikar 2001). The survey results confirm this trend and figures show that 90% of the responding companies have company Web sites that advertise the company’s products and services.

Intra-disciplinary mode of document exchange in construction organisations: Any construction project involves the production and exchange of a large number of documents and drawings at both inter- and intra-organisational level. A high percentage (73%) of the respondents said that e-mail is the most popular medium for the exchange of documents internally within their organisation (Figure 2), while FTP (File Transfer Protocol) is the least likely. It can be seen that the method for exchange of documents/drawings internally, largely depends on the size of the organisation itself. While larger organisations use e-mail as the preferred choice, SME’s (Small to Medium-sized Enterprises) exchange documents by hand.

Interdisciplinary mode of document exchange: The survey findings show that e-mail, fax and post are the most popular methods of exchanging information between construction disciplines (Figure 3). However, the most preferred method of communication could not be conclusively derived from these results. This could be because; depending on the document type, the preferred medium for inter-disciplinary document exchange may vary. For example, most companies’ exchange documents such as specifications and project drawings...
electronically, while the exchange of documents such as Bills of Quantities and technical calculations is seldom done in an electronic format.

![Figure 3: Interdisciplinary Mode of Document Exchange](image)

**ROLE OF IT WITHIN CONSTRUCTION COMPANIES**

The main focus of this part of the survey was to examine the role of IT within the surveyed construction organisations and to establish the impact of IT on the organisation’s day-to-day activities. Of the surveyed organisations, 73% of architectural and engineering firms have a dedicated IT department and a definitive IT policy. It is evident that majority of the responding contracting companies, have IT managers, but no well-defined IT policy.

The successful introduction of any new technology depends upon the receptivity of the staff (Rivard 2000). The results have shown that the overall attitude towards the implementation of IT is generally positive. In order to establish the attitude of construction disciplines towards implementing IT measures, it was necessary to examine the most common factors that influence investments in this area. The need to improve the efficiency of office administrative work and demands from clients, are rated as the two most likely factors influencing IT investments. Additionally, a high proportion of the respondents (60%) also rate the need to be at the forefront of technical innovation, and demands from staff/employees as factors influencing IT investments. Some contracting organisations are hesitant to invest in IT and even suggested that their company would only be pushed into making IT investments, only if it is a client requirement or they can see quantifiable gains from it, in terms of improved business processes.

The survey questionnaire also tried to establish the extent to which the use of IT can improve the design or construction processes. Figure 4 shows the viewpoint of the respondents regarding the influence of IT in areas such as document quality, document errors, speed of work, interdisciplinary communication and construction business processes. More than 80% of the respondents regard increased speed of work, and improved interdisciplinary communications as the key influences of IT on design and construction processes. The response suggests that IT is currently being used to facilitate faster distribution of construction information. Every time data is re-keyed, it can become a
potential source of error. Also each time data is transferred from one document to another, or entered into an electronic repository, there is a good probability that errors will be introduced into the data (Sharda 2000). Some research studies suggest that businesses can eliminate errors that are caused due to data re-entry using technology tools (Watson and Anumba 1991; Anumba 1996); however, from the survey findings there is little evidence to suggest that the use of IT can reduce construction errors.

![Figure 4: Influence of IT on Design and Construction Processes](image)

Members of the construction industry need a sound understanding of the potential of advanced IT systems in construction if they are to gain business benefits from their use (Construct IT 1996). From the survey results, it is possible to establish the key areas in which productivity has increased because of IT use among the participating companies. By productivity the authors mean an increase in the throughput. When asked whether the introduction of IT has lowered or increased productivity in areas such as company administration, project management and coordination, design and site management and interdisciplinary communication, 93% of the respondents said that efficiency in the area of company administration has increased (Figure 5). The responses also suggest that areas of management such as site management have shown little change in productivity due to IT implementation (67% of contractors reported either very little change or no change).
To establish in which areas future IT investments are most likely, respondents were asked to prioritise the possible IT areas in which their respective organisations are planning to invest within the next two years. Among the possible six choices included (Figure 6), investment in Computer Aided Design (CAD) applications has the highest priority rating. Web collaboration portals, design and document management tools are also amongst the most popular IT systems for future investments, while investment in Virtual Reality (VR) applications has been given the least priority. Previous research studies in the area of VR state that the requirements of specialist skills, dedicated staff, cost of implementation and lack of integration between application packages (e.g., integration between CAD and VR), are the major barriers to the implementation of Virtual Reality systems in construction (Issa 2002); the industry needs to take these issues on board to encourage wider usage.

In order to take on board new technologies it is vital that the benefits of and barriers to the use of these technologies are carefully examined and analysed. A majority of the respondents
consider the use of IT applications to be beneficial for different tasks in the construction process (Figure 7). In the view of more than 50% of respondents, use of IT has helped in improving interdisciplinary communications and financial control, speeded up work and increased the possibility of sharing information. Implementing IT to facilitate better management of project data/documents and streamlining the business process are also seen as benefits. A report by the UK Task Force (Egan 1998) has stated that technology alone cannot provide the answer to the need for improved efficiency and quality in construction. The survey results support this, as more than 60% of respondents do not agree that the use of IT can improve the quality of work.

Figure 7: Possible Benefits of Implementing IT Measures

To establish the barriers to the implementation of IT measures, the respondents were asked to rank the barriers, which in their view are preventing wider implementation of IT within the construction sector. Barriers listed in the questionnaire were collated after a thorough literature review carried out by the authors (Ruikar 2001). The respondents were invited to suggest/specify additional barriers. The results suggest that factors such as high cost of initial investment, lack of commitment from management in implementing IT and a lack of interest from company decision makers, are seen as the main barriers to IT implementation. Also, the low profit margin of construction companies is regarded as a barrier to the adoption of IT tools. Majority of respondents do not regard IT-related security issues, regular upgrades of software or hardware, and possible information overload as major barriers. The following section explores the uptake of e-commerce applications in the construction sector, the associated benefits and barriers.

E-COMMERCE IN CONSTRUCTION

By establishing the extent to which the Internet has influenced the construction industry and examining areas in which e-commerce is currently being used, it is possible to gauge the
industry’s changing attitude towards using technology. The section on computer usage in construction companies has shown that a high percentage of staff has access to e-mail. Also, the most common use of the Internet is for the exchange of information using e-mail services (Figure 8).

![Internet use chart]

**Figure 8: Use of Internet in Construction**

The Internet is an efficient medium to promote a company’s products and services. A majority of the companies (80%) have a dedicated company website and use the Internet for company promotion. The survey outcome also suggests the Internet is being widely used for retrieval of construction-related information. About 50% of the respondents also use web-based collaboration tools. An interesting observation is that a high percentage of the responding manufacturing companies do not use the Internet for strategic activities, such as customer relationship management (CRM). Also, very few firms use the Internet for financial transactions such as billing and invoicing (6%), online tendering (10%) and purchase orders (7%).

According to many leading experts (Anumba et al. 2000; Elliman and Orange 2000; Alshawi and Ingirige 2002), the Internet has the potential to transfer complex information accurately, speed up transactions and provide instant access to information from anywhere and at anytime. One section of the survey questionnaire was therefore aimed at establishing the industry’s view of the potential benefits of e-commerce. The questionnaire presented ten
possible benefits and encouraged the respondents to include additional benefits. The results indicate that most respondents have a neutral view of the benefits of e-commerce to construction (Figure 9), with a majority of respondents unsure of the exact benefits of e-commerce to their respective organisations.

![Figure 9: Benefits of Internet E-commerce](image)

Unlike other industries, the construction industry has been relatively slow in the uptake of e-commerce. It was therefore essential to obtain the industry’s viewpoint on the main barriers to e-commerce in construction. Issues related to Internet security and a lack of standards for information exchange across networks, as the two main barriers for using e-commerce. This could be one of the main reasons for the limited use of the Internet for financial transactions such as billing and invoicing, online tendering and purchase orders. Although security issues have been considered as a top priority at cross-disciplinary level, these are not viewed as high priority in IT implementation, which is usually within the organisation itself. Cultural issues, associated with the transition from traditional methods to the use of new tools, are also seen as a major barrier. Other issues associated with using the Internet, such as the invasion of privacy and unsolicited mail are, however, not seen as major deterrents for e-commerce adoption.

CONCLUSIONS AND FUTURE WORK

The survey results revealed that there is a considerable usage of IT applications in the day-to-day working of most UK construction organisations and the level of IT investments largely depends on the size of the organisation. The results show that most firms use email as a
vehicle to communicate with peers. It has also shown that although the Internet is being used to obtain construction related information and data, the construction industry has been relatively cautious in the use of the Internet as a mechanism to conduct day-to-day business. Many in the construction industry believe that the future of e-commerce in construction is still quite unclear and the objectives for using e-commerce technologies in construction have not been clearly defined. This may be due to the lack of a well-defined business process model that integrates e-commerce with the existing infrastructure of construction companies. In order to adopt IT and e-commerce strategies into the day-to-day working of construction projects, companies will have to radically alter the traditional processes of managing construction projects and also the way in which project partners collaborate and communicate with one another. It is therefore, essential to study and examine the effects of incorporating e-commerce and IT based applications into the construction business process. One of the benefits of adopting e-commerce can be a streamlined and more efficient construction business process that uses electronic tools for information exchange and data flow. There is potential for research in the area of development of business strategies for the effective adoption of new technologies such as e-commerce in construction.

Although e-commerce and IT usage can be beneficial to construction there are several outstanding issues such as security that need to be addressed. Reliance on computers requires the working environment to be secure. The high degree of computer dependence and newer systems such as networking and the Internet have made it essential for organisations to invest in computer security systems. Organisations must develop policies to detect computer attacks and prevent computer-related crimes. Barriers to electronic commerce such as security and privacy issues are being further rectified through the introduction of new legislation and data encryption standards. When projects are managed using on-line collaborative tools a huge database of information is created. On completion of the project the data needs to be archived (currently on CD-ROMs). There are concerns about future accessibility of this data when current technologies become obsolete. Thus construction-sector organisations should take measures to ensure continued access to project information (Berning and Diveley-Coyne 2000).

The following recommendations can be made based on the study presented:

- There is potential for conducting future research in the area of development of business strategies for the adoption of e-commerce, including the most appropriate e-commerce business model(s) for the construction industry.
- Construction organisations need to explore the new opportunities offered by e-commerce and re-engineer their business process to maximise the benefits.
- Changes that occur in the construction business process due to the adoption of IT and e-commerce measures need to be continually monitored and documented so that a best practice strategy for their adoption in construction can be formulated.
- As e-commerce is still in the early stages of implementation in most construction organisations there are very few performance measurement tools available to quantify the benefits. More performance measurement tools need to be developed as the technology usage matures.
Based on the findings of this survey, literature review and interviews work is currently in progress to propose a representative construction business process model that uses the principles of BPR. This model proposes the use of IT and Web-based tools in the construction business process with specific focus on construction suppliers and end-users. Clearly, the construction industry has much to gain from the adoption of IT and e-commerce. Greater investment in the enabling infrastructure and in staff training is vital if these benefits are to be realized. The survey results indicate that the UK construction industry has an unclear understanding of the possible benefits of e-commerce. Thus, if the short-term and long-term benefits of adopting e-commerce technologies are made clearer and are found to be profitable, then all barriers to its adoption can be more readily addressed.

REFERENCES


PERSONALIZED CROSS-PROJECT WORKFLOW APPROACH FOR MULTI-PROJECT PARTICIPANTS

R. Scherer¹, M. Keller², and K. Menzel³

ABSTRACT

Considering the special requirements of the planning process in the building industry, a workflow management system should accomplish two major functionalities. It should on the one hand control all process information of one project, and on the other hand assist the user by organizing his daily work in different projects. Thereby it has to be taken into consideration that the process information should be transparent to all participants and internal processes should be hidden to external partners.

This paper describes the steps towards a workflow system especially designed for the requirements in the building industry allowing users dynamic interaction with the system in order to adapt the project workflow to any unforeseen impact on the project progress. Project activities and user activities are synchronized permanently by the system.

KEY WORDS

Personal workflow management, virtual enterprises, ifc 2x process model

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INTRODUCTION
The construction industry in Germany is based on divers organizational structures. More than 90% of the companies have less than 10 employees. Furthermore, design and construction time is very short, generally less than 1 year. Therefore an engineer is usually involved in simultaneous projects. This means a project is not independent from others but all projects are interlinked with each other via the individual engineer to some extent. This also may explain why projects are always hampered by ad hoc changes of available human resources and the engineers are hampered by different software technologies of different projects which they have to manage in order to be able to participate in these projects (Scherer 2000).

Considering these new planning process structures, higher demands to workflow management systems that control and support the processes within a project are set up. Furthermore, workflow applications should be able to support the user in managing his tasks not only within one project but also across project boundaries. One requirement for such personal process management and planning system is to control the individual tasks of an engineer while considering the constraints of different project’s workflows. Such a personal workflow system must be capable to manage multi-project participation in different virtual enterprises with different workflow server systems.

Additionally, there is a need of a personalized workplace with easy access to data, information, and knowledge of each engineer. Furthermore the process information should be transparent to all participants of a project whereas internal processes and data should be concealed to external partners.

APPROACH
In the construction industry there are no workflow management systems (WFMS) known supporting cross project workflow integration for multi-project participation. In order to develop a personal process planning system several requirements have to be taken into consideration:

1) Since the system has to be integrated into an environment of different workflow servers a standardized format for the exchange of process information has to be used.

2) In order to model the project workflow, a description language for business processes should be applied.

3) The overall architecture for the workflow management system should meet two major requirements. The engineer has to have access to the information of the project while his personal data has to be controlled independently.

4) Methods have to be developed for merging different project workflows into a personalized workflow that supports the user in organizing his work more efficiently.
EXISTING THEORIES AND SPECIFICATIONS

IFC PROCESS MODEL

The ifc-model (IAI 2001) is a project model that represents the description of a building. Beside the structural information of the building (e.g., the product model) the ifc-model has been extended to cover information for planning, construction and maintenance processes. Figure 1 shows the User and the Workflow Management elements of the ifc-model.

![Figure 1: UML Notation for User and Task-Management part of ifc 2x](image)

BUSINESS PROCESS MODELING

In order to describe a business process, for example the planning of a building, methods like IDEF-3 can be applied. These methods are used to model business processes with its information like time, sequence, data and person as the most important pre-requisites for WFMS.

IDEF-3 describes a method for the creation of a structured, graphic model of the current state, respectively target state, in a general form. The application of the IDEF-3 method leads to a model that is made of hierarchically structured diagrams, texts and a glossary. A diagram is composed of boxes for the functional description, as well as input, control, output and mechanism arrows which define the boundary conditions of each function (Menzel and Keller 2000, IDEF3 1995).

WORKFLOW REFERENCE MODEL

The principal basis for the design of a project and process management system is the Workflow Reference Model developed by the Workflow Management Coalition (WFMC 1995). The Workflow Reference Model provides one possible standardization approach for workflow management systems ensuring consistent understanding and implementation. Thereby the individual components are separated and communicated by prescribed interfaces (Figure 2).
Figure 2: Workflow Reference Model (WFMC 1995)

The Workflow Enactment Service is in the center of the Workflow Reference Model. This service may consist of one or more Workflow Engines in order to support the creation and execution of workflow instances. By using these interfaces the different components like Process Definition Tool, Workflow Client Application and Invoked Application access the Workflow Engine.

CRITICAL PATH METHOD

The Critical Path Method (CPM) based on procedures of the graph theory has been developed for coordination and optimization of workflow processes. CPM optimizes several individual activities which are part of the workflow. If some of these activities require other activities to be finished before they can get started, then the project becomes a complex network of activities. By applying the Critical Path Method on such an activity net one can determine [Domschke and Drexl 1998]:

- the completion time of a workflow
- which activities are ‘critical’ in that project, meaning that they have to be done with high priority or otherwise the project will take longer due to the cross linkage

To calculate the critical path as well as the float of the project the different activities have to be drawn as arrow diagrams. Then, beginning from the ‘Start’, the Earliest Start (ES) and Earliest Finish (EF) values for each activity will be calculated. The values in the ‘Finish’ give the shortest time it can take to finish the project (assuming the activity durations are as estimated). Once the forward pass is completed, the backward pass will be calculated. Beginning with the ‘Finish’ the Latest Finish (LF) and Latest Start (LS) times can be determined for each activity. The Critical Path is the path of activities that have no slack (ES = LS) while the free float is the gap between the Earliest Finish and the Latest Finished.
FINDINGS

In order to develop a system that enables the engineer to work more efficiently in different projects, the theories and specifications of the previous section were applied and extended for the special requirements of cross-project workflow management systems.

ARCHITECTURE

Considering the requirements of the planning process in the building industry the WFMS should accomplish two major functionalities. It should (1) on the one hand control all process information of one project and (2) on the other hand assist the user by organizing his daily work in different projects, while the process information should be visible to all participants of a project whereas internal processes should be hidden to external partners.

These functionalities can be provided through the development of a two-layer process management architecture. The architecture will distinguish between the different types of information within a project as follows:

- First layer: Project-centered information layer
- Second layer: Personal processes and data layer

Figure 4 describes how the two-layer architecture for the project and company workflow can be implemented. This architecture is based on the Workflow Reference Model and uses a relational database management system (RDBMS) as Workflow Engine. Built-in procedures within the Workflow Engine will match the data between the project workflow and the personal workflow.
The project workflow will be developed and controlled by the project manager with a project planning application whereas the engineer can access modify his personal workflow engine with his personal workflow client. Built-in procedures will monitor the change in the project workflow as well as in the personal workflow in order to synchronize them.

**PROCESS MODEL**

Based on the ifc 2x model for user and workflow-management an IDEF-3 Model of the planning process can be developed. In this model the different attributes according to the project, workplans, and tasks have to be specified.

- **Project** ⇒ compilation of workplans
- **Workplan** ⇒ compilation of tasks
- **Task** ⇒ Assignments for one person with defined start and end
  - **Times** ⇒ consisting of: Early Start/End and Late Start/End
  - **Role** ⇒ a role is the combination of person, organization and skills
  - **Information** ⇒ data obtained during the project has to be assigned to one task
  - **Application** ⇒ a certain application can be assigned to a task, if possible

By using ifc 2x as data format for the business model it can also be used as the exchange format between the project and the personal workflow server.

**PERSONAL WORKFLOW**

When working in different projects, the engineer may be confronted with the problem that he has to perform different tasks simultaneously, while only being able to work at one task at a time. Therefore, a personal workflow with the restriction of no parallel tasks has to be
created. To achieve this, the critical path as well as the float are calculated for each project. Afterwards the user’s tasks will be separated and merged together into a personal workflow. This process is illustrated in Figure 5.

Figure 5: Synchronization of planning processes

In this example the calculated floats are sufficient to arrange non-critical tasks in the gaps between the critical ones. In cases that an overlapping of different tasks is inevitable by the restrictions provided by the project schedules, a delay within the project will emerge. Mechanisms for user driven re-arrangement of workflows should be designed minimizing the influences of dependent tasks.

Figure 6 describes an approach to calculate the minimum delay for one person with three different tasks in three projects. In this approach each possible solution for arranging the tasks will be calculated. Afterwards the delays are summed up. The version characterized by the minimum delay is the solution of this optimization process.
Unfortunately, the number of versions that have to be calculated will rise exponentially with the number of parallel tasks. Therefore it is recommended to apply heuristic optimization methods.

**DEVELOPED APPLICATION**

The proposed approach for generating a personal workflow management in the virtual enterprise has been developed and prototypically implemented within the EU project ISTforCE (IST-1999-11508). The developed Personal Planning Service (PPS) will help to establish a coherent solution for personalized planning of activities and work processes while supporting the engineer in getting the relevant information related to tasks and projects he participates in.

The core of the developed WFMS is the workflow engine based on an information model adopted from the ifc 2x standard. Furthermore, procedures will be developed to control the coherence of processes and data within the database.

The PPS client, developed as a JAVA application, will represent the users personal workflow and the project workflow in a table as well as in a GANTT-Diagram. This presentation gives the engineer a comprehensive overview about the projects he is involved and the tasks he has to accomplish. If a conflict in a project occurs the user will be informed by the PPS so that he has the opportunity to react and rearrange the current workflow.
By integrating the Product Model Server as well as the Document Management System (DMS) into the PPS the workflow will not only contain information about time, status and dependency of a task, it furthermore extends the workflow by the view on the product model and the documents. Thereby the user will be provided with comprehensive knowledge about the information generated by his preceding tasks.

CONCLUSION

In the building industry there is a need for a non-standard workflow management system that focuses on the engineer instead on the project. The engineer as the binding element between different projects should be supported through this system by organizing his tasks and information in different projects.

Project activities and user activities should be synchronized by the system while providing each user with a transparent view on the activities of the whole project. This allows the user to decide how to organize his individual tasks.

The discussed approach and the implementation of a prototype have demonstrated that such a personal planning system can be developed. There is still a lot of work to accomplish. On the one hand the applied procedures for synchronizing the personal workflow with the project workflow have to be improved. On the other hand the system has to be tested on real projects to evaluate if all eventualities that can occur during a project have been thought of.
REFERENCES


INFORMATION AND PROCESS FLOW IN MODELS OF PRECAST CONCRETE DESIGN AND CONSTRUCTION

Rafael Sacks¹, Charles M. Eastman², and Ghang Lee³

ABSTRACT
Thirteen detailed process models of precast producer companies’ engineering design, production and erection procedures have been prepared as part of an effort to re-engineer the information-dependent processes of precast design and production. Under the guidance of the research team, precast company experts each modeled their company’s processes using the custom-built ‘GT-PPM’ process-modeling tool. The tool allows modelers to define detailed information inputs and outputs for each process activity and produces models that are machine-readable. We present and discuss methods of comparison and extraction of common information items from the heterogeneous process models collected. We also discuss the advantages and difficulties encountered in using the Design Structure Matrix and other methods to analyze the models and to track the information flows through the activities. The project is ongoing: a second round of process modeling to capture the companies’ future processes, incorporating the envisaged software and data model, will begin once an upgraded version of the GT-PPM tool is completed.

KEY WORDS
Process modeling, precast prestressed concrete, construction management, engineering design, product model.

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INTRODUCTION

The North American Precast Concrete Software Consortium (PCSC) was formed with the goal of providing its 23 member companies with fully integrated engineering and production information systems. The working plan calls for the parallel development of a Precast Data Model (a product model – Eastman 1999) and of new 3D integrated precast modeling software tools that will be capable of automating much design and engineering work, as well as populating the Precast Data Model. In the initial phase of the PCSC project, process modeling was employed to provide the basis for specification of the software tools (Eastman et al. 2001). The specification incorporates five of the seven key features of concurrent engineering listed by Anumba et al. (2000): parallel product decomposition, concurrent processing, minimized interfaces, transparent communication and quick processing.

Process modeling is considered an effective tool in support of implementation of concurrent engineering in construction (Dubois and Jägbeck, 1999, Karstila and Björk 1999, Karhu 2001). The PCSC member companies recognize that achieving their objectives (reducing engineering lead-time and improving production economies, through effective application of the new information systems) will require re-alignment of their business processes and human resources. In this regard, process modeling serves as a catalyst, aiding companies to understand their current processes and prepare their businesses for the re-engineered processes that fully integrated IT tools will support.

The next section briefly introduces the GT-PPM (Georgia Tech Process for Product Modeling) tool, presents the project goals and the models of the precast industry, and describes three methods of analysis – at the activity level, at the information item level, and using the Design Structure Matrix (DSM) method. We discuss the perspectives gained on the Precast Industry and examine the models and their analyses. We conclude with the directions for the next phase of this ongoing research.

PROCESS MODELS OF PRECAST DESIGN, ENGINEERING AND ERECTION

Graphical process modeling languages such as IDEF0 (NIST 1993), SADT charts (Marca and McGowan 1987) and UML activity and sequence diagrams (UML 1997) are common in construction process modeling (Anumba 2000, Poyet et al. 1994, Karhu 1997, Karstila 2001). The process-models are usually assembled by researchers based on interviews with industry experts, with the attendant problems of elicitation (Dawood 1996). The graphic nature and layout of the languages allows only superficial treatment of the depth and complexity of information that is typically communicated in construction projects. The resulting models are not machine-readable; thus no automated consistency check or other validation is possible. The primary orientation to graphical description limits the support a model can provide for product data modeling. Specifically, they cannot be used as a means for directly deriving data used to generate structures within the product data model.

For these reasons, we elected to build a process-modeling tool that would allow the industry experts – representatives of each of the member companies – to build their own process models directly, and to incorporate detailed information flows in the models. The tool is called ‘GT-PPM’. It is implemented in Microsoft Visio 2000. Users describe process flow with activity, information flow, decision, connection, static info source, material flows
and other basic symbols. The symbols distinguish between high-level and detailed activities, and between activities that are within the project scope and those that are external to it. Users are also required to define the information input and output for each detail activity (the interface is shown in Figure 1). The information items are drawn from a domain-specific menu, and each individual company model has at its root a generic high-level model. We prepared both the information item menu and the high-level model with the modelers’ participation and consensus.

Figure 1: GT-PPM version 1.1 – detailing information flow for an activity

Figure 2 shows the high-level model used for the first phase precast concrete industry process modeling. Our goals in developing the GT-PPM tool were to:

- capture information flows at a level of detail useful for both software application development and for product modeling,
- explore methods to synthesize information from diverse company process models for these purposes, without compromising individual company models,
• develop methods to verify and check process models for completeness and accuracy,
• encourage individual companies to undertake process modeling as a means to plan the re-engineering of their own organizations.

Figure 2: Generic high-level Precast Concrete industry process model

After a number of iterations of submission and review, 13 detailed models were prepared. Eight covered the full range of precast design, engineering, production and management activities common in standard sub-contracting scenarios from project acquisition through to erection; three described design-build processes, with emphasis on the conceptual design stage; and two modeled only design activities. The models and measures of their complexity are listed in Table 1.

Table 1: Precast company process models and their complexity

<table>
<thead>
<tr>
<th>Model Statistics</th>
<th>Full Process: Sub-contracting</th>
<th>Full Process: Design-Build</th>
<th>Design Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Number of Detailed Activities</td>
<td>154</td>
<td>269</td>
<td>57</td>
</tr>
<tr>
<td>Average Number of Information Flows</td>
<td>232</td>
<td>476</td>
<td>89</td>
</tr>
<tr>
<td>Number of Models</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
The models reveal similarity in their engineering and production processes, and diversity in their business and management processes. The typical shapes (cross-sections), functionalities and contents of the precast assemblies and pieces, as revealed by the design and analysis activities and their information items, are generally similar across the companies. The main differences in their management processes are found in different approaches to contracting, different quality control procedures, and different degrees of integration between engineering, production and management information systems. Three levels of analysis applied to the models are described below.

**Activity Level Analysis of Process Detail**

All of the models use the generic high-level model as their starting point (Figure 2). Although modelers added additional intermediate layers of high-level activities, every detailed activity can be traced to one common high-level activity. Using this as a starting point for analysis across company models, a list of new intermediate level activity groupings was compiled for each high-level activity. The level of detail for each grouping was then assessed based on the number of individual detailed activities used in each. In general, the results indicate which high-level activities were superfluous, which required further elaboration, and whether the process flows at this level were correct. One of the aims of this analysis was to identify commonalities across companies’ processes and to derive a middle-level process model of precast design and construction, based on the initial high-level model.

**Information Item Level Analysis**

Although the generation, use and change of value(s) of any individual information item can be tracked through any particular model, different models use differing subsets of the whole information item domain. Grouping items according to functions or physical objects facilitates comparison of the ways in which information is used across different companies. For each grouping, we compare the earliest appearance of common information items across the common high-level activities of the models, as illustrated in Figure 3. When differences are found, examination of the information included in one model, but excluded from the other, aids interpretation.

Table 2 presents a small sample of the results of such an analysis for information related to design at the structure level in each of two detailed models (denoted ‘Company A’ and ‘Company B’)

4. 278 unique information items appeared in Company A model; 868 in Company B model. Of these, 129 were common.
Figure 3: Common information items compared across common High-Level activities

Table 2: Generation of structure design information items in two precast process models.

<table>
<thead>
<tr>
<th>Structure Design Related Information Items</th>
<th>Company A</th>
<th>Company B</th>
</tr>
</thead>
<tbody>
<tr>
<td>analysis: load type, loads, multiple load cases, reactions at nodes and elements</td>
<td>Do Detail Design</td>
<td>Check QA</td>
</tr>
<tr>
<td>activity management cost for activity</td>
<td>Project Control</td>
<td>Acquire Project</td>
</tr>
<tr>
<td>activity management production erection equipment description</td>
<td>Project Control</td>
<td>Prepare Project Schedule</td>
</tr>
<tr>
<td>applicable code spec standard name</td>
<td>Acquire Project</td>
<td>Check QA</td>
</tr>
<tr>
<td>applicable code spec standard title</td>
<td>Do Detail Design</td>
<td>Check QA</td>
</tr>
<tr>
<td>design requirements description</td>
<td>Acquire Project</td>
<td>Check QA</td>
</tr>
<tr>
<td>design requirements type</td>
<td>Acquire Project</td>
<td>Check QA</td>
</tr>
<tr>
<td>grid or shape: centerlines, complete parametric shape, explicit 2d shape, grid layouts</td>
<td>Acquire Project</td>
<td>Do Detail Design</td>
</tr>
<tr>
<td>Identifier</td>
<td>Acquire Project</td>
<td>Do Detail Design</td>
</tr>
<tr>
<td>Location &amp; orientation</td>
<td>Acquire Project</td>
<td>Do Detail Design</td>
</tr>
</tbody>
</table>

**DSM ANALYSIS**

The Design Structure Matrix (DSM) (Steward 1981) enables analysis and optimization of the sequences of project activities in relation to the information interdependencies between the activities. This is particularly useful in concurrent engineering as it exposes unnecessarily
long iteration loops, which are generally detrimental to concurrent design (Denker et al. 2001). The required input declared for each activity in the GT-PPM models, which must flow to the activity on information flow arrows, represent information dependencies; a dedicated export function is provided in the GT-PPM tool to directly write a DSM matrix representation of the activities and the flows. The matrix is processed using a DMS analysis tool (Browning et al. 2000) in Microsoft Excel. Figure 4 shows (a) a portion of a process model and (b) an associated excerpt from the matrix after partitioning.

During the model development stage, the technique was applied to locate errors or omissions in the models: activities without any input information flow are easily identified, as are activities that produce neither information nor material product. In completed models, the DSM allows identification of iteration loops in the process. In such situations, the information required for the earlier activity is at first unavailable. Reasonable values must be assumed for certain parameters (e.g. ‘Select Trial Type and Geometry’). Processing can then continue until an evaluation is made (‘Check Combined Loading Capacity’). If the results based on the assumed values are inadequate, flow returns to activity in which they were assumed for iteration of the process between these two activities. As an example, a common situation found in a number of models was that spatial interference between prestress strands,
reinforcement, embeds or block-outs inserted in a piece was not checked rigorously until the components were physically inserted in a mold in preparation for casting. Failure in this check results in a long feedback loop to detailed design.

DISCUSSION

PRECAST INDUSTRY PERSPECTIVES

The results of analysis of the process models can be summarized in three general observations:

- There is significant diversity in the companies’ management processes. The sequence of activities such as project acquisition, detailed design, cost estimating, quality control and scheduling vary from company to company. Certain of the differences in focus are due to differences in building type, contract type, company policies and existing management information systems.

- There is little variation in the types and characteristics of the basic precast piece ‘building-blocks’ produced by companies across the industry. The information items used to describe precast pieces and the embeds, reinforcement, prestressing, connection hardware, etc. typically cast into them, are essentially the same for all companies, irrespective of the contract type or management processes.

- The processes include a significant number of interfaces as information is passed from department to department within companies; internal and external review procedures add additional interfaces. While automation is common within most activities, communication between them is mostly dependent on paper drawings and reports.

The level of detail of engineering design performed prior to award of contract is an example of the management related discrepancies between company procedures. At the extremes, some companies estimate their jobs in specific estimating activities, which have as input only the basic information supplied by the client; while others perform comprehensive general arrangement and piece design and analysis activities in order to obtain accurate quantity estimates. This can presumably be attributed to different management attitudes to the trade-off between the direct cost of estimating and the accuracy of bidding (and a presumed attendant improvement in the chances of securing the contract). The issue is of significance in terms of the overall goal of re-engineering precast concrete software based on integrated 3D models; in such an environment, automating design and detailing should enable a precast producer to adopt the second strategy.

The second observation suggests that definition of a precast industry product data model is feasible. Investigation of the differences in the use of certain information items revealed that these were mostly related to terminology rather than substance. For example, some companies used the term ‘control-number’ to denote specific locations for precast pieces in a building design layout; others used it as an identifier for individual precast pieces after they are stripped. This and other cases were resolved in the precast data-dictionary, which was refined in this phase, and is a precursor to development of the product model in the next phase.
The last observation underscores the primary goal of the PCSC: it indicates that re-engineering of the information process, including increased concurrency and elimination or improvement of interfaces, has the potential to reduce the costs and duration of precast concrete production.

**ANALYSIS OF INFORMATION RICH PROCESS MODELS**

Empowering industry representatives to build their own process models, rather than distilling elicited information into a single process model built by researchers, allowed expression of the diversity inherent in different companies’ procedures. At the same time, those parts of the process that are fundamental to the technology of precast design and construction could be identified. As a result, we expect that the precast data model and the software tools that will be developed will more effectively support the range of nuances in company practice across the industry.

Capturing detailed information input and output for process activities, and using a tool that ensures that users maintain information flow consistency, represents a new approach to process modeling in support of defining product data models in the AEC sector. In the first phase, it has provided the information necessary for development of a data-dictionary. In the next phase, we expect to develop techniques for deriving a product model directly from the process models.

Three types of process flow constraints are relevant in models of project processes such as precast concrete design and production: information dependencies, physical precedence and policy precedence. Only material and information flows were provided in the tool, resulting in nonsensical results from DSM analysis for a small number of specific scenarios in the process models. Also, the standard DSM tool does not allow ‘hard-wiring’ of the process flow required for material or other physical flow constraints – an improved partitioning algorithm seems necessary. For example, consider the activity ‘Test Release Strength’ in the precast piece fabrication process described in Figure 5. Information flows to it from ‘Detail Design’ (on a separate page) and from ‘Pour Bed’. As a result of other, longer information loops, involving feedback from fabrication to design, the partitioning algorithm placed this activity before the ‘Pour Bed’ activity, which is clearly illogical.

For physical precedence, material flow symbols should be used. Modelers should be encouraged to carefully consider whether any flows in their process do not in fact carry information, and to avoid indiscriminate use of information flow arrows. For the purposes of analysis for process improvement, ‘soft’ policy constraints should be relaxed to allow exploration of more concurrent processing alternatives. The development of process models that are optimal over time or resource allocations may become possible.
SECOND PHASE PROCESS MODELING

The first phase of process modeling supported specification of the next-generation precast software tools. In the next phase, each company will be asked to prepare a model reflecting the company’s business processes as envisioned after incorporation of the re-engineered software and product data models in their business processes. Apart from the direct benefit to the companies themselves, these are intended to provide rich information for the data modeling effort and to aid the developers of the new software. To these ends, we have introduced a number of changes:

- An additional, middle-level of detail has been added to the generic high-level process model to be used as a basis by all the modellers. The aim is to deepen the levels at which comparative analyses can be made; it also facilitates specification of new software applications being developed for parts of the process.

- The information menus are more comprehensive and richer in their ability to express aggregations of objects and attributes. They also allow synonyms to cater for variation of terminology across companies.

Figure 5: ‘Fabricate’ detail page of a typical process model
• Improvements in the GT-PPM tool, intended to enhance the robustness and consistency of the models’ process and information flows, include explicit ‘real-time’ checking of information flow consistency, automated connection symbols, and information detailing for static information sources (Lee et al. 2002).

CONCLUSIONS

The development of the GT-PPM tool succeeded in encouraging thirteen precast producing member companies of the PCSC to prepare detailed and information-rich process models of their management and engineering practices. The models are machine-readable, allowing automated checking of the consistency of information flows and analysis of the processes described. We plan to make intensive use of this technology in the next phase of the research – development of a precast data model. We have refined the data-dictionary describing the precast domain through analysis of the information items and their groupings in different models. DSM analysis offers a method to examine and potentially re-engineer the sequence and interdependence of the activities, although it is limited by the constructs available at present.

Precast engineering and production, as practiced by the participating companies, is relatively uniform from the point of view of the physical products; it is relatively diverse in the range of business and management procedures that characterize different companies. In many cases, models that appear to be similar under superficial observation of their activities alone are in fact quite different in terms of the ways in which information is used within those activities. Intra-company communication remains heavily dependent on paper-based communication. The processes contain many interfaces both within each company and externally to it. These conditions reinforce the starting assumptions of the PCSC – that re-engineering and integrating the information processes of the industry may result in significant reduction in engineering lead-time and improvement of overall efficiency.

ACKNOWLEDGEMENTS

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REFERENCES


NIST (1993). “Integration Definition for Function Modeling (IDEF0)”, *Federal Information Processing Standards Publication (FIPS) 183*, National Institute of Standards and Technology, Gaithersburg, Maryland, USA.


USING PROCESS SPECIFICATION LANGUAGE FOR PROJECT INFORMATION EXCHANGE

Jinxing Cheng¹ and Kincho H. Law²

ABSTRACT

There are many project scheduling and management programs employed in the construction industry. Standards-based translation is one way to achieve interoperability. This study evaluates the applicability of the Process Specification Language (PSL) for exchanging project information among different applications. PSL has been initiated by National Institute of Standards and Technology (NIST) and is emerging as a standard exchange language for process information in the manufacturing industry. In this paper, we explore how PSL can be extended for exchanging project information for construction applications.

KEY WORDS

Process Specification Language, PSL, ontology, information exchange, project management

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INTRODUCTION

As the use of information technology increases in the construction industry, the capability of software applications to interoperate has become increasingly important. A construction project usually involves volume of project information from different sources. There are many construction applications that could be employed in a construction project. For example, as shown in Figure 1, different members of a project team may use Primavera Project Planner (P3)™ or Microsoft Project™ to schedule the project, Vite™ to simulate the project organization, Timberline’s Precision Estimating™ to estimate project cost, and 4D Viewer (McKinney and Fischer 1998) to view the progress of construction. In a distributed but concurrent engineering environment, information interoperability plays a significant role in project management.

Figure 1: Construction Applications in Project Management

There have been many ontology standards, such as STEP, IFC and aecXML, which aim to provide interoperability among different applications. Most of the existing ontology standards, however, focus more on product data rather than process information. Process Specification Language (PSL) is one such emerging standard proposed by NIST (National Institute of Standards and Technology) that is designed specifically to exchange process information among manufacturing applications. This study explores the applicability of using PSL as an interchange standard for construction project management applications.
EXISTING ONTOLOGY STANDARDS

For the last two decades there have been many efforts from the industry, academia and standards organizations to propose ontology standards for data exchange, such as STEP (ISO 1994), IFC (IAI 1997), aecXML (IAI 2002), etc.

- **STEP** (the Standard for the Exchange of Product Model Data) is a product data integration standard to enable information exchanging among different applications (Fowler 1995). STEP is based on the EXPRESS language, which enables STEP to provide unambiguous, computer interpretable representation of product data. EXPRESS is a data definition language that is used to represent the structure of data and any constraints that may apply to it.

- **IFC** (Industry Foundation Classes) is a data representation standard for defining product data for architectural and construction applications. There have been efforts to extend IFC from product modeling to support data for cost estimating and project management purpose. In short, IFC is designed to exchange data among AEC/FM (Architecture, Engineering, Construction and Facilities Management) applications. IFC is also based on the EXPRESS language.

- **AecXML** was initially proposed by Bentley Systems in 1998, and is now part of the effort under the IAI (International Alliance of Interoperability). AecXML includes XML schemas to describe information specific to the design, construction, and operation of buildings, plants, infrastructure, and facilities. Efforts have been made to share the IFC and aecXML developments.

The ontology standards described above focus mainly on product data and do not have extended information about process and task specifications.

PROCESS SPECIFICATION LANGUAGE (PSL)

The development of Process Specification Language (PSL) is motivated by two basic reasons. First, there are not many existing standards for process information exchange. Second, current ontology standards lack a formal logic to define relationships and constraints. Every ontology in PSL is either formally defined (for non-primitive terms) or there are a set of axioms associated with it to constrain the meaning (for primitive term).

PSL is based on KIF (Knowledge Interchange Format), which is designed for knowledge interchange among disparate computer systems. KIF has declarative semantics, and is logically comprehensive (Genesereth and Fikes 1992). When combined with domain specific ontology, KIF has the expressive power to represent knowledge.

Figure 2 shows the overall organization of PSL, which includes the PSL core, the PSL outer core and PSL Extensions (Schlenoff et al. 2000).

- The PSL core is a set of axioms based on KIF. The PSL core includes four basics classes: Object, Activity, Activity_Occurrence and Timepoint. Relations are defined among the classes, for example:
  
  \[(\text{occurrence-of activity-occurrence activity})\]
  \[(\text{before timepoint timepoint})\]
• PSL outer core consists of a small set of extensions, which are generic and pervasive in their applicability. The extensions in the PSL outer core include Subactivity Extension, Activity-Occurrence Extension and States Extension. Relations can be defined using the PSL outer core extensions, for example:

$(\text{subactivity-occurrence} \ \text{activity-occurrence} \ \text{activity-occurrence})$

$(\text{subactivity} \ \text{activity} \ \text{activity})$

• PSL extensions include ontology modules such as generic activities, ordering relations and schedules. Each module is motivated by a set of applications and covers concepts in certain domain. Below are some example relations in the PSL extensions:

$(\text{before-start} \ \text{activity-occurrence} \ \text{activity-occurrence} \ \text{activity-occurrence})$

$(\text{before-start-delay} \ \text{activity-occurrence} \ \text{activity-occurrence} \ \text{activity-occurrence} \ \text{activity-occurrence} \ \text{activity-occurrence} \ \text{activity-occurrence} \ \text{duration})$

![PSL ontology diagram](image)

Figure 2: PSL ontology

**PSL FOR PROJECT MANAGEMENT APPLICATIONS**

While PSL was initially created mainly for manufacturing industry, it can be applied to construction project management applications by extending the ontology to model the essential project information.

Ontology (Guarino 1997) is an explicit specification of some topic. In other words, ontology includes a set of terms and the relationships among those terms. When two programs need to exchange process information, they not only need to agree on a representation language for the interaction, but also need to agree on an ontology in their domain. In our research we select Vite™ as the benchmarking application to evaluate the applicability of PSL in the construction industry. Vite™ is a project and organization modeling system designed to assist in developing organizational structures and identifying potential problems with project cost, time, or quality. It takes traditionally qualitative organizational management theory and builds a model that incorporates rough quantitative measures.
For a typical construction project, project information includes three basic categories: scheduling information, resource information and cost information. Currently PSL ontology covers primarily the scheduling part. After analyzing the information needed and the output by Vite™, extensions to the current PSL ontology are designed to include organization module, construction activity module and project module (Figure 3).

One of the main concerns in the ontology extensions is that we should not include too many application specific concepts in the PSL ontology. PSL is not designed to capture all the information needed by each application. There should be some other internal schemas to represent all the application specific information. On the other hand, PSL should be sufficiently general and capable to exchange the essential process information among different applications. We should define the concepts, which are also relevant to other applications, generalize those concepts, and include them in the PSL ontology extensions.

The organization ontology focuses on organization structure, roles, authority and empowerment (Fox et al. 1996). An organization can be individual or group of individuals to which organizational attributes and relations are associated with. Some examples of the relations defined in the organization extension are:

\( (\text{Experience} \ \text{actor} \ \text{string}) \)
\( (\text{Director} \ \text{group} \ \text{actor}) \)

Construction activity is an activity in a construction process associated with certain attributes, such as priority, uncertainty, and dependency. Examples of the construction activity extensions include:

\( (\text{Priority} \ \text{ConstructionActivity} \ \text{number}) \)
\( (\text{Dependency} \ \text{ConstructionActivity} \ \text{ConstructionActivity} \ \text{number}) \)

Project ontology extension covers general project information, for example:

\( (\text{ActivityAssignment} \ \text{project} \ \text{ConstructionActivity} \ \text{actor} \ \text{number}) \)
\( (\text{WorkDay} \ \text{project} \ \text{number}) \)

For each new term in the ontology extensions, we provide some definition or axioms to define and limit the interpretation of the new term. As an example, the following shows the definition and the axiom for dependency defined in the ontology extensions.

**Definition of Dependency:**
\( (\text{defrelation} \ \text{dependency} \ (?a1 \ ?a2 \ ?n) := \)
Axiom: The dependency relationship is transitive.
(\forall (a1 a2 a3)
  (\Rightarrow (dependency a1 a2 n1)
    (dependency a2 a3 n2)
    (\exists n3 (dependency a1 a3 n3)) )
)

INFORMATION EXCHANGE USING PSL

_MAPPING CONCEPTS BETWEEN PSL AND CONSTRUCTION APPLICATIONS_

It is not unusual that the same term is often associated with different meanings in different applications. To exchange project information, first we need to map the concepts in different applications onto PSL ontology, so that they are PSL compliant. Table 1 shows some terms that are related to activity relationships in PSL and Primavera Project Planner (P3)TM.

<table>
<thead>
<tr>
<th>Concepts in P3</th>
<th>PSL Ontology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successor</td>
<td>Successor</td>
</tr>
<tr>
<td>Predecessor</td>
<td>after-start</td>
</tr>
<tr>
<td></td>
<td>after-start-delay</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The example in Figure 4 shows that activity B is the successor of activity A with relationship type FinishToStart in a construction project P from P3TM.

![Figure 4: Successor relationship in P3](image)

Suppose that the time lag is 3 days between activity A and B, then the successor concepts can be expressed using PSL ontology as:

(activity-occurrence A)
(activity-occurrence B)
(subactivity-occurrence A P)
(subactivity-occurrence B P)
(after-start A B P)
(after-start-delay A B 3)
EXCHANGING PROJECT INFORMATION USING PSL

To exchange project information among different construction applications, we need to develop wrappers for each application (Figure 5). The wrappers are used to retrieve information from applications and convert the information into the PSL format. In addition, the wrappers are also used to parse information from PSL files and transfer the information to applications.

![Figure 5: PSL in the information exchange](image)

The basic process of using PSL for project information exchange can be illustrated in Figure 6. Although the basic processes for the PSL wrappers are essentially the same, different implementations are necessary to build the wrappers for different construction applications.

![Figure 6: PSL wrappers](image)

- For Vite™, the concepts in Vite™ are mapped onto the formal ontology described using PSL, which explicitly and unambiguously defines all terms introduced within the language. We then parse the relevant information stored in the Access database using Java Database Connectivity (JDBC), translate the information into PSL according to a set of rules, and create a PSL file. For the PSL to Vite™ translation, the information in the PSL file is parsed and rewritten...
into VNB (Access database) file format. Vite™ could open the VNB file and start the simulation.

- For P3™, Primavera Automation Engine (RA) is employed. RA is a set of object-oriented, OLE 2.0-based API, which allows object-oriented programming access to the P3™ scheduling engine and other applications. We use RA to communicate with P3™, such as retrieving project information from P3™ and transferring project information to P3™. Figure 7 shows a sample code to illustrate the PSL wrapper for P3™.

```vba
Sub setActivities()
    Dim I As Integer
    Dim bret As Boolean
    For I = 0 To numActs - 1 Step 1
        Dim act As Object
        Set act = m_Project.Activities.NewItem()
        act.ActivityID = acts(I).id
        act.description = acts(I).description
        act.OriginalDuration = acts(I).duration
        act.EarlyStart = acts(I).beginof
        bret = m_Project.Activities.Add(act)
    Next I
End Sub
```

Figure 7: Sample code of the PSL wrapper for P3

- For Microsoft Project™, VBA (Visual Basic for Application) is employed. The process here is very much similar to the development of communication protocols for Primavera P3™.

- For 4D Viewer (McKinney and Fischer 1998), the scheduling information from the PSL file is retrieved and converted into the format required by 4D Viewer.

DEMONSTRATION OF INFORMATION EXCHANGE USING PSL

EXAMPLE 1: CHIP DESIGN SCENARIO

We select a sample project from Vite™ to test PSL as an interchange standard for process information. Vite™ is a project and organization modeling system designed to assist in developing organizational structures and identifying potential problems with project cost, time, or quality. A Vite™ project is composed of a traditional CPM diagram and additional links showing failure dependence, reciprocal information and management structure.

The example scenario (Figure 8) is to design and fabricate a chip set for a new personal digital assistant (PDA) product within a tight schedule. There are 12 activities in this project. Among the 12 activities there are three milestone activities: ‘Start Project,’ ‘Ship Tapes to Foundry’ and ‘Fab, Test and Deliver.’ The activity ‘Design_Coordination’ is to maintain the overall control of the project.
USING PROCESS SPECIFICATION LANGUAGE FOR
PROJECT INFORMATION EXCHANGE

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Figure 8: Original CPM diagram in Vite

Using PSL as an interchange standard, we successfully exchange scheduling information among Vite™, Primavera Project Planner (P3)™ and Microsoft Project™. Figure 9 shows some selected logic sentences from the PSL file particular to this Project.

```
(and
  (project TUTO)
  (doc TUTO "TUTORIAL Project")
  (beginof TUTO 9/18/1998)
  (subactivity-occurrence ID100 TUTO)
  …)
  (and
    (activity-occurrence ID190)
    (doc ID190 "PartitionChip & Floor Planning")
    (beginof ID190 10/19/1998)
    (duration-of ID190 42)
    (before-start ID190 ID130 TUTO)
    (before-start-delay ID190 ID130 TUTO 0)
    …)
)
```

Figure 9: Sample PSL file

Figures 10 to 12 illustrate the generated schedule in Vite™, P3™ and Microsoft Project™. Figure 10 is the original Gantt chart of the sample project in Vite™. Figures 11 and 12 show the regenerated project schedule in P3™ and Microsoft Project™, respectively. As shown in the figures, project information is being exchanged successfully among these three applications. Activities have the same start date and duration in all three applications. The critical paths are also the same in all three applications.

Figure 10: Original Gantt chart in Vite
EXAMPLE 2: MORTENSON CEILING PROJECT

To test the scalability and applicability of PSL as an interchange standard, the Mortenson Ceiling Project is employed to illustrate the information exchange process. The Mortenson Ceiling Project is a portion of the construction of the Walt Disney Concert Hall, built by Mortenson Construction, and designed by Frank O. Gehry & Associates.

We use PSL as the data standard to exchange project information among P3™, Microsoft Project™, and 4D Viewer (McKinney and Fischer 1998). There are 191 activities and 459 dependency relationships in the project. In the PSL file of this project, there are more than 2000 logic sentences.

Figures 13 to 15 show selected results of this example demonstration. Figure 13 is the original Gantt chart of the ceiling project in P3™. Figure 14 is a snapshot of construction progress in 4D Viewer on March 25, 2001. Figure 15 is the modified Gantt chart regenerated in Microsoft Project™, where the duration of activity 18T1-33201 has been changed from 1 day to 40 days. As shown in Figure 15, the scheduling information originally in Primavera Project Planner (P3™) is successfully regenerated in Microsoft Project™ using PSL.
CONCLUSIONS

Many construction applications can be employed in a construction project. To exchange project information among different construction applications poses a challenge for collaborative team members of a project. Although PSL has originally been designed
specifically for process information related to manufacturing applications, we have successfully extended the ontology to model essential construction project information. We have developed PSL wrappers for some typical construction applications, and successfully exchange project information among those applications, such as P3™, Microsoft Project™, Vite™ and 4D Viewer (McKinney and Fischer 1998). Our research shows that PSL, an emerging interchange standard for manufacturing applications, is also a promising candidate interchange standard for construction project management applications.

Our successful demonstration also shows that PSL can be used for information exchange among different applications, thus facilitating concurrent engineering processes in construction from different team members. Process information can be shared among various applications by different teams of different disciplines.

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REFERENCES


TOOLS AND SERVICES INTEGRATION PLATFORM OF THE ISTFORCE PROJECT

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ABSTRACT
The Internet is enabling new paradigms of collaboration among humans and is offering new perspectives for observing the role of software that is being used in the design and planning processes. It is that of a service, available on-line through the Internet. Several dot-com companies have tried to capitalize on the developments and quite a few have failed in the process. These developments are also allowing rethinking the approaches to concurrent engineering in construction.

ISTforCE is a European 5th Framework Information Society project (2000-2002) aimed at developing technologies for the next generation of such collaboration platforms. The acronym stands for "Intelligent Services and Tools for Concurrent Engineering". The substantial novelties in the ISTforCE are that (1) it provides a personalized human-centred environment, enhancing current, less flexible project-centered approaches, (2) it sets up an open collaboration platform where new services and tools may be easily integrated and where providers of engineering information, services and tools meet managers, engineers and architects, (3) it makes flexible and customizable object level data exchange possible and (4) it provides infrastructure such as on-line e-business that can be seamlessly established at all system levels – for legal and financial transactions.

KEY WORDS
project webs, web portals, product data exchange, service-service communication, collaboration, concurrent engineering, construction.

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INTRODUCTION

Over the last 10-15 years, the fragmented nature of the construction profession has been one of the main topics of construction informatics research. Computer integrated construction and concurrent engineering have been the goals that envisioned primarily the information processes of the industry to become more efficient and less error-prone. For example in the ToCEE project (Scherer and Turk 1999) such a concurrent engineering environment has been set up.

CURRENT SITUATION

In the second part of the 1990s the Internet has been intensively explored as a platform, which could be used to exchange information between architects, engineers, construction managers, and the construction companies on the building site (Ouzounis 2001; Turk et al. 2000b; Weisberg 2001). However, the Internet is still typically used to support only the non-core, non-value-adding activities in the construction value chain. By core value adding activities we understand those that result in the detailing of design and construction plan specification such as CAD modelling and drafting, proportioning, planning. These activities are not done on or using the Internet. The Internet is increasingly used as a communication platform (email) and a source of information (web pages), but it has not yet been used as a place where the actual engineering work is carried out. Indeed, several companies have started offering Internet based project support on a rental basis. On web sites, such as Bricsnet, Citadon and several others, companies and groups of companies can rent shared project space, with functionalities for publishing and retrieving design files, establishing security and access rights, versioning and configuration management, redlining, safe communication channels, mailing lists, notifications etc. (Bricsnet 2001; Buzzsaw 2001; Citadon 2001; Conject 2001; Weisberg 2001). However, in spite of many advanced features, they provide only the file exchange infrastructure, communication, perhaps some work scheduling, redlining etc. Moreover, these services only support information sharing and communications which are essential for collaborative design, but by themselves do not enhance design or planning information. They are overheads!

No tools are available that can actually get the core engineering or architectural work done—work that contributes to the evolution of the design or construction plan. They are project centred: they allow creating the support for one or several projects and provide project centred interfaces. Most engineers in construction practice work on several projects at the same time. Also, they only allow for file/document level information exchange, but can hardly manage more structured project information into which research and industrial communities invested substantially.

GOALS OF ISTforCE PROJECT

ISTforCE (EP IST-11508) is a 31-month EU 5th framework IST project, running from February 2000 through to August 2002 with an overall budget of about 4 million Euro. The partners come from Germany, France, Italy, Spain, UK, The Czech Republic and Slovenia. ISTforCE is developing and testing ideas that would raise on-line collaboration in construction to a new level (Scherer 2000). The main project objective is to establish an open
concurrent engineering platform with access to intelligent services and tools that will support two main needs of engineers:

**Individuality.** Due to their different roles, expertise and personal experience engineers have different individual preferences and capabilities. They need services that can support their individual creative work in flexible and adaptable fashion.

**Multi-project work.** In construction, engineers typically participate in several virtual enterprises in parallel, working concurrently on several projects at the same time. This aspect of construction IT is in strong contrast to other industries and requires appropriate non-standard solutions.

**NOVEL APPROACHES IN ISTforCE**

In accordance with these objectives ISTforCE addresses a number of novel approaches in Internet-based collaborative work:

*Human-centred instead of project-centred collaboration.* Today’s existing web-based collaboration environments handle a project as the main unit or aggregation of information – one project, several participants. However, in construction it is typical that engineers work on several projects at once - one person, several projects. The environment should therefore be adapted to such work. Typically, the engineer needs to take into account the overlaps among the current projects as well as the historic information from previous projects.

*Open services platform.* A different approach to web sites, which are open but limited in functionality, is currently observed in the development of proprietary frameworks built around a set of comprehensive design tools, such as AutoCAD 2000i (Goldberg 2001). However, no single company, not even Microsoft, AutoDesk or Primavera, is in a position to provide all the services and tools required to support all working tasks in a construction project. They provide collaboration infrastructure, but not integrated with the variety of heterogeneous tools engineers, architects and managers would need. In contrast, on the ISTforCE platform, the providers of software, services and tools meet with the end-users. The platform is open and allows for integration of design software, proportioning tools, analysis tools, CAD systems etc. but, as a platform on the Internet, it can only support companies that can provide services, tools and software on the Internet. In construction, where 97% of the companies employ less than 20 persons, a typical company is an SME. It cannot be expected that these companies have an Internet strategy or a person with the required knowledge to allow for this company to participate in the new economy. Therefore, ISTforCE is providing such a service for them.

*Product data based integration.* When different software becomes available through a single platform, it makes a lot of sense for this platform to provide for information exchange among this software. ISTforCE builds on the last two decades investment into product modelling to support the exchange and sharing of structured information conforming to the industry standard IFC schemas (Wix and Liebich 2001).

In short, ISTforCE caters for both the end users and the service providers and brings them together onto one open platform.
PERSONALIZED CONCURRENT ENGINEERING SERVICES PLATFORM - CESP

Central to the ISTforCE approach is the concept of an open, personalised Concurrent Engineering Services Platform (CESP). The platform (Figure 1) provides the end user with access to arbitrary services and tools available on the Internet, that he needs to solve his engineering tasks. He does not have to care as to where these tools are actually located. Tools can be plugged into the platform and are registered by an information service. They are flexibly exchangeable. They can either be downloaded and hosted at the user’s desktop or they can be accessed remotely. An e-Commerce service (EOS) with a billing component takes care about the financial aspects, and a training and on-line human support service (TOS) provides continuously accessible help about any IT aspects of the platform.

Furthermore, the platform can provide the end user with easy access to information and data from different project servers. The interoperability service manages data and information operability and a knowledge-based model access service provides an engineering like communication interface (Scherer and Katranuschkov 1999) based on a new engineering ontology developed in the scope of the project (Gehre and Katranuschkov 2000). Thus, the platform is a bridge between information and tools, located anywhere throughout the Internet.

Figure 1: Illustration of the ISTforCE platform and its components – the user is in the centre

SOFTWARE ARCHITECTURE

ACTOR VIEW

Basically, the platform is a place where four main groups of people meet:

- Engineers and architects who design and plan. They need the platform for (1) collaboration tasks such as to communicate to each other, exchange information, co-ordinate work, and (2) for their actual design and planning work. They design and plan using different CAD tools and accessing different data and knowledge bases.
• Managers who manage the design and planning process. Project information managers need to manage projects, monitor architects and engineers, assign and supervise tasks, as well as tools and services.
• Chief information/internet officers who provide information technology support for the construction projects. They need an easy, scalable, and configurable way of setting up this infrastructure.
• The providers of knowledge, information, and software. Service and tool providers need channels through which they can sell their products. They know their trade, but may not be experienced with Internet tools. They expect an infrastructure they can rent so that they can concentrate on their core business.

**Layer View**

ISTforCE architecture is shown in Figure 2.

Figure 2: ISTforCE architecture: three kinds of services are made available

**Layer 1:** On top, the three classes of users are shown. They are accessing the services and tools through the ...

**Layer 2:** personal platforms, which may be any of the following: service launcher, personal planning tool and a web portal. These provide the interfaces to other services.

**Layer 3:** On the third layer from top there are engineering services such as code checking tools, virtual testing lab, rentable software and any other software that has been made compatible with the ISTforCE platform.
Layer 4: On the fourth layer there are infrastructure services of three kinds: (1) Project infrastructure services provide product and process model information, (2) people-projects integration services provide uniform access to work on several projects, (3) generic infrastructure services provide functionality that is not construction specific, for example payment, help-desk generators etc.

Layer 5: Finally, on the lowest level there are core information services - the only services that are central to the platform. They manage the vital information about the people, companies they work for, projects, roles that people have in projects, and the services offered through the platform.

The components higher on this "sandwich" diagram use the components which are lower down.

Business Level View

Three principal use levels (business cases) can be identified, emphasising the flexibility and the scalability of the ISTforCE approach. These are:

- Business level 0: Integration of services
- Business level 1: Integration of services and project data
- Business level 2: Virtual enterprise.

Level 0 enables the use of local engineering applications and remote engineering services via common GUI and APIs. Project data support as well as workflow support are not provided and have to be organised by the user on his own responsibility. However, all third-party services can be appropriately billed as needed. The involved components of the ISTforCE infrastructure and their principal interoperability are illustrated on Figure 3.

Figure 3: Principal interoperability at business level 0 “Integration of services”
All active components are shown by white boxes, and the numbered arrows indicate the basic operation sequence. Unidirectional communication is denoted by single-arrow lines, and bi-directional communication by double-arrow lines. The information exchange is consistently based on XML, even where file exchange, such as STEP physical files, is involved.

Business level 1 extends the features of business level 0 by enabling model access and project data management services. The latter can be accomplished in two ways: (1) directly, by using the specialised model access services client (MAS/C), which provides ontology-based browsing and explanation capabilities, and (2) through a local or remote application, provided that it supports the appropriate features. The involved components and interoperability are different for the two cases as shown on Figures 4 and 5.

**Figure 4:** Principal interoperability at business level 1 “Integration of services and project data” for the case of directly accessing the project data repositories with the help of MAS/C.

**Figure 5:** Principal interoperability at business level 1 “Integration of services and project data” for the case of accessing the project data repositories by a remote engineering service.
In the first case, the most probable users are project managers who need fast and condensed project information. The second case is more typical for designers who have to work with detailed data. However, common to both cases is that the user has to be authenticated and that he/she does have a project role. Correspondingly, the user access rights can be properly determined to suit user needs and responsibilities.

Business level 2 exposes the full features of the platform. It further extends level 1 by enabling multi-project workflow and information support. Here the user has both a project and an enterprise role. All services are accessed through the workflow client (PPS/C), and tasks can—ideally—be fully coupled with project data support. At this level, all components and the related interoperability aspects come into the play (Figure 6). However, at this level, too, all transactions are based on the common well-defined interface specifications and are generally not visible to the end user who can concentrate on his/her actual practical tasks.

Figure 6: Principal interoperability at business level 2 “Virtual enterprise”. At this level the full functionality of the environment is used.

PROTOTYPE ENVIRONMENT

The prototype include between 10-15 custom built components and a growing number of software that was adapted so that it can be used through the platform and work with product-level based data. The main interface to it all can either be a web browser with possible standard plug-ins (e.g. VRML) and extension languages (Java, JavaScript) or the local applications such as the personal planning system client or the service launcher. However, the four actors have each their unique adaptable user interface.

Services need to talk to each other. Due to very different requirements, the lowest common denominator is TCP/IP networking. Some services may use standard protocols (e.g. ftp or http), some proprietary solutions. CESP itself uses the operating system and other server resources, such as a database engine and core Internet services, such as mail and ftp.
However, even more important than these technology issues is the common commitment of the services to a lean, easy to implement high-level communication language based on a system-wide ontology (Guarino 1998), which is consistently defined in ISTforCE in terms of XML (Katranuschkov 2001; Katranuschkov et al. 2001).

The currently developed prototype environment (Figure 7) includes the principal features of all infrastructure services, a set of three rental services, each exploiting different provider alternatives, and a few selected applications demonstrating the features of the system design concepts. Project model data are according to IFC 2x (Wix and Liebich 2001) and the IAI ST-4 project (IAI 2001; Weise et al. 2000). The core infrastructure services of CESP have been encoded as a set of Perl scripts which are fully operational as well and provide XML/SOAP-like interface to the many services that they need to support (Turk et al. 2000a).

The environment is under development. Components are being tested and in fact deployed as regular business offerings of the industrial partners. The whole integrated platform is being tested and verified in a synthetic demo scenario which includes collaborative and concurrent multi-project work.

Figure 7: (left) Main page of ISTforCE. The four vertical tabs denote the four main groups of users. Clicking on each vertical tab opens up a specialised screen for the respective actor. (right) CIO Manager interface allowing to create and reuse various databases.

CONCLUSIONS

In this paper, the architecture and some of the prototype work on a platform for collaborative engineering on the web has been described. The platform is not only concerned with the horizontal integration of the architects and engineers, but also with a vertical integration of all professions providing construction related services on-line consultants, software houses, etc. The demonstrated platform enables the collaboration in construction projects and provides a market place for selling construction related services, tools and knowledge. It allows for any construction service or software provider to take part in the new economy.

The key components of the infrastructure for collaborative work are information exchange and communication tools, and the key components of the infrastructure for the
providers are service templates, e-Commerce tools and security tools, so that they could concentrate on their core knowledge and not on Internet technology. In the remaining subsections we perform a brief SWOT analysis of the proposed approach.

**Strengths.** The developed approach, at least as envisaged conceptually, integrates the entire profession in which small and medium companies are in a large majority. It provides them with a new model of doing business and all the necessary infrastructure. As such it can integrate the fragmented construction profession.

**Weaknesses.** The prototype is created using tools that allow for rapid prototyping but lack the robustness of the tools with which a professional platform would be built. Currently, we have not addressed issues like security and privacy.

**Opportunities.** Central management of project information should result in a digital archive of previous project. This could enable better reuse of old project data, analysis of the processes as well as synthesizing new knowledge about construction. The data could be used to support full life cycle of the structure. To service providers, a common point of entry for all users and a centralised user tracking could lead to better understanding of the users and their needs.

**Threats.** Companies providing core collaboration services could be tempted into using project data, either discretely or synthetically, to learn about the participants and about the ways construction work is done, and therefore exploiting the implicit knowledge of the construction companies using the services and benefiting from them. An open collaboration platform where many small providers of services and tools can offer these to construction professionals is also a threat to established players in the field, who are interested in exploiting collaboration platforms to extend their monopoly in one segment of the market (e.g. CADD or project planning) over the whole industry. Such portals are also threatened by the general lack of economic soundness on the Internet. In order to establish market shares, dotcoms are offering services nearly for free. Engineering consultants and software authors cannot operate at a similar price. In addition, the ease at which information can be exchanged digitally is likely to cause an information saturation and overload. Designers and planners will be receiving a growing number of messages, files, calls, just because sending out a digital copy of a floor plan is so much easier than drawing out a paper version and mailing it. Therefore, advanced filtering on both sender's and receiver's end will be required as well. All these threats include topics for future research.

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**REFERENCES**

Bricsnet (2001). Bricsnet Solutions
http://www.bricsnet.com/about/solutions/default.jsp?site=1
Buzzsaw Inc. / Autodesk Inc. (2001). Project Point™
(http://www.buzzsaw.com/content/products_and_services/ProjectPoint/default.asp).


IAI (2001). ST-4 Structural Analysis Model and Steel Constructions
(http://www.iai-ev.de/projekte/documents/pdf/IFC_ST4.pdf,


COLLABORATIVE SYSTEMS AND CE IMPLEMENTATION IN CONSTRUCTION

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ABSTRACT

The potential benefits of Concurrent Engineering (CE) to the construction industry generated considerable interest in the 1990s. But this interest seems to have waned in recent years, raising questions about the relevance of CE in the light of current developments in internet-based systems such as project extranets. Given that CE is an approach which incorporates various concepts and methodologies, this paper assesses whether it is being implemented through various collaborative systems, which are currently in use in the construction industry. The ‘systems’ considered here are partnering and project extranets, which respectively, deal with organizational and technological support for multi-disciplinary project teams – key aspects of the CE philosophy. The assessment of partnering and project extranets in relation to CE principles is used to explore the wider issues of CE implementation in the construction industry. It is concluded that since the implementation of CE will be reflected in a variety of tools and methodologies that may not bear the CE label, it is unrealistic to expect a more coherent and concrete implementation of CE in construction. Thus CE is best promoted as a ‘philosophy’ rather than as discrete tools and techniques.

KEY WORDS

CE implementation, construction, partnering, project extranets

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INTRODUCTION

There is now wide acceptance that the concept of Concurrent Engineering (CE) is relevant to the Architecture, Engineering and Construction (AEC) industry. The key principles of CE include integrated and concurrent processes, multi-disciplinary teamwork, early consideration of lifecycle issues in product development, and up-front requirements analysis. Is it acknowledged that the implementation of these principles of CE, through the use of various techniques, tools and technologies (e.g., Quality Function Deployment, Design for X’s, CAD, CAE, etc.) will bring about much needed improvements to both the construction process and the quality of construction products (Kamara et al. 2000).

This realization has been the motivating factor in the development of tools and technologies for CE in Construction (CEC). A review, published in 2000, of developments in the implementation of CEC (Kamara et al. 2000) concluded that although progress was being made, much needed to be done if the reported benefits of CE (i.e. reduced project times and costs, increased quality, etc.) in other industries are to be realized in construction. In particular, it was suggested that CE research needed “to be broadened in scope [from a more technology bias] to consider other vital areas such as client requirements processing, organizational structures [and] contractual arrangements among members of multi-disciplinary teams”. It was further suggested that “varied efforts need[ed] to be coordinated to avoid duplication of efforts and disparate pockets of CE implementation”. The implicit assumption in the review by Kamara et al. (2000) was that a coherent and concrete implementation of CE is to be pursued. However, the growth in the use of various collaborative systems such as project extranets (Construction News 2002), which may reflect CE principles but are not described as such, might suggest that perhaps a more ‘unified’ implementation of CE is unrealistic.

This paper therefore assesses the extent to which various collaborative systems reflect CE principles. This assessment is used to discuss wider issues on CE implementation with regard to the measurement of implementation levels, and the relevance of the ‘CE’ label. The collaborative systems considered are partnering and project extranets, which respectively deal with aspects of organizational and technological support for virtual construction teams – key CE principles. Collaborative systems are defined and a brief review is provided on how these systems are used in the AEC industry. This is followed by a more detailed description of partnering and project extranets and an assessment of the extent to which they reflect CE principles.

COLLABORATIVE SYSTEMS

The term ‘collaborative system’ is used here to refer to processes, techniques, templates, technologies and software applications used to support the work of virtual construction teams. The development of such systems is motivated by the need to integrate the otherwise fragmented AEC industry and foster collaboration among the multi-disciplinary teams that operate within a temporary organization to deliver construction projects. The desire for collaboration is also influenced by the realization that the adversarial culture that prevailed in the construction industry is detrimental to its efficiency and profitability. Collaborative systems can be broadly categorized into organization- and technology-based systems.
ORGANISATION-BASED SYSTEMS

These refer to systems that focus on defining the relationships, roles and liabilities of construction team members and include: procurement strategies, contract types and improved processes. Integrated procurement strategies (such as Design and Build, and Management Contracting) and their associated standard forms of contract are examples of organization-based collaborative systems. The interest in, and development of, integrated procurement strategies preceded those for the implementation of CE in construction. However, because they focus on defining the relationships of multi-disciplinary teams, they are relevant to CE.

Other initiatives in organization-based systems include the Generic Design and Construction Process Protocol (commonly known as the Process Protocol) (Cooper et al. 1998) and Project Partnering. The Process Protocol (PP) was motivated by the need for project teams to “work to an agreed set of processes and procedures”. The PP, which is as yet not widely used in the industry, is designed to facilitate a whole project view, progressive design fixity, and the adoption of a consistent process by all team members (PP 2002).

Partnering is an approach which provides the basis for multi-disciplinary teams to work collaboratively. It is extensively used in the construction sector of the UK oil and gas industry (Anumba et al. 1997). It is increasingly being used in the mainline construction industry in the UK since legislation was passed to remove the restriction on government institutions (the biggest client of the industry) to use lowest-price tendering (Construction Manager 2002). The development of a standard form of contract for project partnering (PPC2000) by the Association of Consulting Architects (ACA) will further encourage the adoption of partnering. PPC2000 was first published in September 2000, and it is now estimated that “£2bn [US$3bn] worth of construction is administered by PPC2000 contracts, most of it for housing associations” (Construction Manager 2002). Since partnering is specifically designed to foster collaboration, and given its increasing use, this concept is considered in more detail later in the paper as an example of a collaborative system that might reflect CE principles.

TECHNOLOGY-BASED SYSTEMS

These refer to the technologies and software applications that are designed to support group collaboration on construction projects. This family of products/technologies, etc. is commonly referred to as “groupware” (Chaffy 1998). Figure 1 shows the evolution of collaborative technologies in relation to the development of computer support technologies. It is observed that the development of collaborative applications is made possible by advances in network and client-server technologies. ‘Lower-end’ collaborative technologies such as email are now common place. Groupware applications (e.g., Lotus Notes and Microsoft Exchange) are also increasingly being used on construction projects (Gellatly et al. 2000).

‘Higher-end’ (web-based) applications (Figure 1) such as intranets and project extranets have experienced a dramatic increase in their use in recent times. A survey of extranet service providers, which was published in March 2002, indicated that over 3000 projects (approximately 60,000 users) in the UK now use a project extranet (Construction News 2002). A similar survey in August 2001 gave a figure of 1,500 projects, a 100% increase in 7
months. These figures suggest a growing trend in the use of project extranets, and their adoption on a majority of construction projects.

Figure 1: Evolution of Collaborative and Supporting Technologies (Chaffy 1998)

**IMPLICATIONS FOR CONCURRENT ENGINEERING**

The increasing use of collaborative systems will (arguably) bring about improvements to the construction process. But within the context of CE, their use poses a number of questions. If these systems are increasingly becoming the norm in the industry, to what extent do they reflect the principles of CE? If collaborative systems can bring about the required improvements to the construction process, is CE still relevant? The rest of the paper will address these questions by describing partnering and project extranets, and assessing the extent to which they reflect CE principles.

**PARTNERING**

Partnering is “a management approach used by two or more organizations to achieve specific business objectives by maximizing the effectiveness of each participant’s resources” (JCT 2001). The approach is based on:

- Shared mutual objectives and compatible benefits
- Agreed problem resolution methods
- Shared risks according to who can best manage them
• An active search for continuous measurable improvements

• Managing the client/supplier relationship proactively

The partnering process, which must involve all participants in the project, is comprised of three stages (JCT 2001): the agreement to use partnering; setting up an initial workshop to agree objectives and problem resolution methods; and further partnering workshops during project execution to maintain and improve teamwork. Partnering deals with people, relationships and communication. Team members “choose to live by the spirit, rather than by the letter of the law” (Hellard 1995). Thus it “attempts to establish working relationships, whereas the contract establishes the legal relationships” (JCT 2001).

Implementation of partnering is either through a non-binding charter, a binding agreement, or a bespoke partnering contract (JCT 2001). Repeat clients with a huge construction program (such as BAA plc) have implemented it through five-year framework agreements with a number of suppliers. In a non-binding charter, signatories to the charter agree to act: “in good faith, in an open and trusting manner, in a co-operative way; in a way to avoid disputes by adopting a ‘no blame culture’, fairly towards each other, and valuing the skills and respecting the responsibilities of each other” (JCT 2001).

Non-binding charters, by their nature, are open to abuse and the introduction of the partnering contract (PPC2000) has been welcomed by different sectors of the industry (Construction Manager 2002). Key features of the PPC2000 (ACA 2000) include the following:

• Team-based multi-party approach by allowing the client, constructor, consultants and key specialists (subcontractors) to sign a single partnering contract.

• Integrated design/supply/construction process by providing for the early selection of a project partnering team and the collaborative finalization of designs, prices and members of the supply chain.

• Incentives, systematic risk management and non-adversarial problem resolution.

There are obviously many ‘teething’ problems as the industry moves from an adversarial culture to a ‘win-win’ culture based on mutual and shared objectives, but as mentioned above, there are already signs that partnering is taking root in the industry. The specific features of partnering and its relationship to CE are discussed below.

PROJECT EXTRANETS

Project extranets (or project websites) are “dedicated web hosted ‘collaboration and information spaces’ for the AEC industry that support design and construction teams” (Augenbroe et al. 2001). These sites are hosted by a growing number of ‘service providers’ which include Architec Ltd., 4Projects, Bidcom, BIW Technologies, Buzzsaw, and BuildOnline. Project extranets allow users to share, view and comment on project documents (e.g., drawings, minutes of meetings, specifications, plans, etc.) via a web browser (Sturley 2002). A simplified model of the interaction between project organizations and a project website is illustrated in Figure 2. This shows a ‘shared project space’ to which participating firms can share, view and comment on project-relevant information. This model reflects a
situation where the site is hosted by an application service provider (ASP) such as the ones listed above. However, some providers allow users to host the site on their (the user’s) web server.

Figure 2: Interaction between project organizations and the shared project space

Project extranets utilize client-server internet technology and therefore require access to a web browser. The facilities for collaboration are wide ranging depending on the service provider, and can (according to Construction News 2002) include any or all of the following:

- Sharing, viewing and commenting (redlining) on documents. The installation of propriety software is not normally required to enable users to view and comment on documents. In this regard all (or most) standard file formats are supported. Concurrent viewing of the same document by multiple users is also possible.

- Document management (to varying degrees) including version control, audit trail of documents, tracking and recording of changes, document locking, and search facilities for document/information retrieval.

- Process management through, for example, automatic notification when any document relevant to a user has been changed or added, the ability to send and receive notices, create and respond to RFIs (request for information), and the management of document approvals and change requests.

- A range of communication facilities such as conferencing, threaded discussion forums, and email.

- Linking of documents with other objects or diary events.

- Integration of third party applications (e.g., enterprise systems) and other hardware such as PDAs (personal digital assistants).
The use of project extranets is obviously faced with many challenges such as data security and legal issues. However, reported benefits in the use of extranets appear to outweigh the challenges. These (according to CPN 2002, Williams 2001) include:

- Reduced design time and design cost through reduced drawing review turnaround, reduced paper and distribution costs, etc.
- Increase design process efficiency
- Transparency in who has posted, received, and reviewed a document
- Removal of bureaucracy in project management
- Minimization of waste through reduction in the number of mistakes and disputes.

The above listings of the functionality and benefits of project extranets are not exhaustive, but they highlight some of the issues that will be used to assess the ‘CE credentials’ of Project Extranets.

COLLABORATIVE SYSTEMS AND CONCURRENT ENGINEERING

This section of the paper assesses the extent to which collaborative systems reflect CE principles. The features of the systems reviewed above will be assessed against the defining principles of CE.

Figure 3 shows a framework for understanding CE. Various tools and techniques facilitate CE strategies, which in turn ensure that the objectives of reducing time-to-market, reducing cost and improving product quality are achieved (CE objectives). The objectives lead to the goals of CE, which are customer satisfaction and a competitive business. Tools and techniques used to support CE are generic and can be used to support other concepts. The objectives and goals are also generic and may be achieved (in varying degrees) by using other strategies. The defining feature of CE, however, is in the mix of strategies used to achieve the objectives of reduced project time and cost, and improved quality. These strategies form the basis for assessing the CE credentials of the collaborative systems discussed in this paper.

Integrated and concurrent processes and tools are at the heart of CE. The classic definition by Winner et al. (1988) refers to “integrated, concurrent design of products and their related processes, including manufacture and support.” Integrated concurrent design involves upfront requirements analysis and early consideration of all lifecycle issues affecting a product, and is achieved through multidisciplinary teams. This implies that for CE, there should be:

- Concurrent and parallel scheduling of all activities and tasks as much as possible.
- Integration of product, process and commercial information over the lifecycle of a project; and integration of lifecycle issues during project definition (design).
- Integration of the supply chain involved in delivering the project through effective collaboration, communication and coordination (getting the right data/information to the right place at the right time and in the right format).
• Integration of all technologies and tools utilized in the project development process (e.g., through interoperability).

**Figure 3: Framework for Understanding CE (Kamara et al. 2000)**

Integration can refer to the “sharing of something, by somebody using some approach for some purpose” (Betts et al. 1995) or more specifically, “the continuous interdisciplinary sharing of data, knowledge and goals among project participants” (Fischer 1989).

There are different types and levels of integration, but the focus here is on project lifecycle integration in relation to: the process and content of information and knowledge, between and within project stages. Table 1 is a matrix of concurrency which can be used to assess the level of ‘concurrency’ within a project team (Prasad et al. 1993).

**Table 1: Matrix of Concurrency (Prasad et al. 1993)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Modes of Interactions</th>
<th>Single User</th>
<th>Cooperating Users</th>
<th>Simultaneous Users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Access own products’ interaction tools or applications (PITA)</td>
<td>Sequential Engineering (SE)</td>
<td>SE</td>
<td>SE</td>
</tr>
<tr>
<td>2</td>
<td>Run against their own data</td>
<td>SE</td>
<td>SE</td>
<td>SE/CE</td>
</tr>
<tr>
<td>3</td>
<td>Access PITA belonging to other work-groups</td>
<td>SE/CE</td>
<td>CE</td>
<td>CE</td>
</tr>
<tr>
<td>4</td>
<td>Access date belonging to other work-groups</td>
<td>CE</td>
<td>CE</td>
<td>CE</td>
</tr>
<tr>
<td>5</td>
<td>Access both PITA and data from</td>
<td>CE</td>
<td>CE</td>
<td>CE</td>
</tr>
</tbody>
</table>
The modes of operation (rows) and the possible work-group configurations (columns) are shown. A cooperating user is “a person who completes the work left unfinished by previous users” (Prasad et al. 1993). Simultaneous users refer to other members of the project team who may access “the same design, tool or application concurrently, or …different versions of product information tools or applications (PITA) at the same time” (Prasad et al. 1993). The level of concurrency depends on the type of interactions, and this increases as one moves from top to bottom and from left to right. It is observed that some situations are described as both sequential and concurrent: when simultaneous users run their own data, and when a single user accesses the PITA belonging to other work groups (Table 1). The interaction will be sequential if two or more users cannot edit and save changes to a document until another user has finished with it, even though they can be working in parallel.

This brief review on the principles of CE will now be used to assess the extent to which the collaborative systems discussed here, reflect CE principles. The context (practice) of the AEC industry will also be taken into consideration.

**PARTNERING AND CONCURRENT ENGINEERING**

As an approach which is intended to foster a spirit of cooperation within a project team, partnering provides an organizational framework for CE. It is therefore relatively easier to integrate the project supply chain within a partnering context, than it is within an adversarial contract environment. Since partnering also facilitates the early involvement of all members of the supply chain, the CE principle of “early consideration of lifecycle issues affecting a facility” is more likely to be achieved than in more traditional procurement. This therefore, is a significant contribution to CE, when considered against the conventional mode of organizing construction project teams – i.e. standard forms of contract.

However, CE is not only concerned with organizational frameworks. Technological support is also required, otherwise the objectives of reduced project time will be difficult (if not impossible) to achieve. Furthermore, the actual scheduling of activities to ensure concurrency is not supported, although the cooperative framework provided can facilitate this. Aspects of CE are reflected in partnering, but it does not embody the entire mix of CE strategies.

**PROJECT EXTRANETS AND CONCURRENT ENGINEERING**

Project extranets provide a ‘shared space’ where project documents and information can be shared. The extent to which project extranets reflect CE principles is discussed below.

There is ‘integration’ of product, process and commercial information over the lifecycle of a project. However, this ‘integration’ is in the sense that all relevant information about a facility can be accessed from a single website; not, for example, in the sense that a CAD drawing incorporates information about fabrication, construction sequence, and other commercial information of a building. Furthermore, while project information is usually available for the entire duration of a project, extranets in themselves do not ensure that lifecycle issues affecting a facility are incorporated during the early stages of a project.

Collaboration, communication and coordination, are also supported, but to varying degrees. Because project participants have a shared space (and discussion forums),
collaboration and communication are possible among them. The support for most standard file formats through specialized viewers provides for communication of project information. But this is sometimes restricted. For example, viewers that display drawings only show a 2D version of that drawing. Users who want to view the drawing in all its views need to download it to their machines if they have the relevant application installed. Some extranet sites also support multiple users to view and comment on the same document simultaneously, facilitating some degree of ‘concurrent working’ (see Table 1). However, they do not allow users to view the tools/applications of other users. It should also be noted that support for communication is mostly in terms of the process, rather than the content and structure of the data being communicated. Support for coordination is also limited; project extranets are essentially document-centric and process/workflow capabilities are as yet not very advanced (Augenbroe et al. 2001). Furthermore some extranet sites do not support a ‘push’ system where users are automatically notified about relevant information.

With respect to the integration of “all technologies and tools”, there is some support for this within extranet sites, to varying degrees. There is integration of, for example, various technologies including internet, client-server technology, email, groupware, document management, search engines, encryption, etc. Within the shared project space, information (documents) generated from a variety of applications and tools can also be uploaded and viewed through a standard web browser. The ‘integration’ capability of extranets may not incorporate all technologies and tools, or complete interoperability between different packages using in a project, but it represents a significant development in this regard.

However, project extranets do not (as yet) facilitate the concurrent and parallel scheduling of all activities. They also do not necessarily facilitate cooperation among project team members. But on balance, they reflect (to varying degrees) key CE principles relating to technology, and to some extent, the actual collaboration between members of a project team.

DISCUSSION

The description and assessment of partnering and project extranets show that both can be considered as “tools and techniques” (Figure 3) that can facilitate the CE strategies of integrated and concurrent processes, multidisciplinary teams and early consideration of lifecycle issues. The reported benefits of project extranets (see above) are also very much the same as the objectives of CE (reduced design/project time, etc.). The fact that the collaborative systems discussed here reflect CE principles is quite in line with the idea that CE is an approach that embodies other methodologies and concepts. But why do we need a ‘CE label’ if these ‘sub-strategies’ can, and do deliver the desired results? If these ‘sub-strategies’ (which do not bear the CE label), are themselves major research agendas is it justified to subsume them under the banner of CE? If CE is made up of all the disparate (but perhaps related) methodologies, how can we measure the extent to which it is being implemented in the AEC industry? These questions will be addressed by considering the relevance of the CE label, and the measurement of CE implementation in construction.

RELEVANCE OF CONCURRENT ENGINEERING LABEL

Although the component concepts of CE (e.g., partnering) are major research/practice agendas in themselves, it is our view that the CE label is still relevant. This is because CE
represents a ‘goal’ which embodies the aspirations for an efficient and truly integrated construction process that delivers value for money to its clients. It also provides a vehicle to integrate the various ‘islands of automation’ under one umbrella philosophy.

‘Concurrent Engineering’ can however, be an unacceptable term to AEC professionals (particularly architects) who do not see themselves as “engineers” because of the erroneous interpretation of CE as being concerned with ‘engineering’ or only with ‘concurrent processes’. A more acceptable term might be “collaborative working” but what is more important is that the ideals and attitudes represented by CE are promoted in the industry, irrespective of the specific nomenclature used. However, to ensure that this happens, it is necessary to use the CE label as a reminder of its principles and goals.

MEASURING CONCURRENT ENGINEERING IMPLEMENTATION IN CONSTRUCTION

Closely associated with the question of a label, is that of measurement. If CE is being promoted in the industry, how do we ascertain whether or not it is being implemented? As was mentioned earlier, there was (and probably still is) an assumption that a concrete and visible implementation of CE is possible, and indeed required in the industry. However if CE is represented in a variety of methodologies, it is unrealistic to expect a precise measurement of how much it is being implemented. As a philosophy that promotes integrated and lifecycle design, judgments about its implementation will have to be subjective. Thus, there will always be the need to periodically assess (as in this paper) how various systems and tools reflect CE principles.

CONCLUSIONS

This paper has assessed the extent to which various collaborative systems (partnering and project extranets) reflect CE principles. These systems respectively, deal with aspects of organizational and technological support for virtual construction teams, which are key principles of the CE philosophy. This assessment revealed that both partnering and project extranets reflect aspects of CE. However, given that these systems do not bear the CE label, the questions relating to the relevance of the CE label, and the measurement of how it is being implemented, were raised. It is concluded that as a philosophy which embodies the aspirations for an integrated and efficient construction process that offers value for money to clients, the CE label is relevant, and must be promoted. It was however acknowledged that because of this, judgments as to the extent of CE implementation in the AEC industry can also be subjective. It is therefore necessary that periodic assessments are made of the extent to which existing and emerging tools, systems, etc. reflect CE principles. This will keep focused the goal of ensuring that the CE philosophy permeates through the culture of the industry for the satisfaction of its clients, and the profitability of construction firms.

REFERENCES

DEVELOPING AEC/FM TRANSACTION STANDARDS

Arezou Pouria¹, Mahmoud Halfawy², and Thomas Froese³

ABSTRACT

Enabling efficient information exchange across different parties involved in AEC/FM projects is regarded as a critical factor that determines the overall success of the project. This paper presents an ongoing research project that aims to define standards for information exchange for the AEC/FM industry. Information exchange between various roles and their applications needs to be formalized and organized. Standardization of the transactions will potentially provide better communication, increased quality and productivity, and reduced costs, delays and legal suits in the industry. The methodology and a classification system of AEC/FM transactions are described. The methodology has been applied to two sample scenarios: a document review process, which happens in many different project stages; and a materials delivery process, where a general contractor, subcontractors, and suppliers need to exchange information in order to schedule material delivery to the site.

KEY WORDS

Transaction standards, interoperability, concurrent project systems, e-commerce

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INTRODUCTION
AEC/FM is a fragmented industry in which many participants need to collaborate with each other during a short period of time. In a typical project, information flows across various processes throughout the project life cycle. The flow of information is a crucial factor for the success of AEC/FM projects. Project processes typically involve a broad range of “transactions. In general, any communication or interaction between different parties can be described as a transaction. Enabling efficient information flow and exchange among project processes would require the formalization and standardization of these transactions.

Transaction examples include: on-line purchasing of materials, requests for information on a job site, and reporting inspection results. Transactions can generally be described in relation to various activities performed by project participants and aimed at achieving specific business objectives. Increasingly, information is exchanged electronically, and it is these electronic transactions in which we are specifically interested. Transaction standards are not generally required for human-to-human communication where the participants have a high capacity to “interpret” the transaction semantics. However, transaction standards are useful for electronic communication that requires more formally structured information; and they are critical for any fully or partially automated transactions.

Since the development of the product and the process happens simultaneously in a concurrent environment, the need to enable efficient information flow and exchange becomes more critical. Concurrent AEC/FM systems emphasize the development of an integrated environment through the entire life cycle of the project where information would flow from downstream processes to upstream project processes. In this regard, communication plays a vital role in streamlining the project activities. Therefore, maintaining the integrity of project data would require formalizing and preferably standardizing communication transactions.

Much of the research throughout the last decade was driven by the need to develop standard industry-wide data models for AEC/FM projects. Different applications used in different stages of the projects by various participants need to interoperate to avoid any loss of information and increase productivity and quality of AEC projects. Interoperability can be described in terms of specific data exchanges, or transactions, that occur among users and applications. There have been efforts underway to standardize the data content of these transactions. However, interoperability also requires that the context of these transactions be standardized.

This paper describes a research project that aims to define transaction standards in AEC/FM industry, which will lead to the ultimate goal of enabling interoperability between the software applications, used across all project phases and to provide the necessary tools to leverage the use of IT in different business processes within the scope of AEC projects.

RELATED WORK
Standard data models are widely recognized as the main enabling technology to implement concurrent project systems. Most notable of these models is the Industry Foundation Classes (IFC), developed by the International Alliance of Interoperability (IAI 2002). IFC is considered to be a mature and comprehensive model that is widely supported and accepted by the industry. The IFC model is based on the ISO 10303 Standard for the Exchange of
Product Model Data (STEP). The goal is to provide a neutral mechanism to be able to describe product data independent from any specific system throughout the life cycle of the product. The IFC model defines an integrated schema that represents the structure and organization of project data to support interoperability among various software tools. The model provides an abstract and conceptual representation of the project data in the form of a class hierarchy of AEC/FM objects. An increasing number of commercial software products support IFCs.

Efforts in recent years through ISO and the IAI have been focusing on defining the syntax and semantics of a standard language. The IFCs and the aecXML effort could be the basis of the future development of the common language for data exchange in AEC/FM industry. Many commercial software tools, such as Autodesk’s Architectural Desktop, Graphisoft’s Archicad, Nemetschek’s Allplan, Microsoft’s Visio, and Timberline Precision Estimator, have already implemented IFC file exchange capabilities.

The industry interest in using eXtensible Markup Language (XML) for data exchange has been increasing rapidly. XML is a standard that specifies the syntax that allows users to define their own markup language. aecXML in North America and bcXML in Europe are two new initiatives that try to use XML for data exchanges (Liebich 2001). Another project within IAI, called ifcXML extraction and evaluation project have been underway to use the previously achieved consensus on data content within AEC/FM industry and apply it to XML based data exchanges. Two important use cases of such effort are to enable the exchange of IFC data files as XML document instances, and to enable the reuse of IFC content and structure within XML based initiatives for data exchange in Construction and FM industries.

In other industries, organizations have used electronic aids to support their data processing tasks for many years. Automatic exchange of data between remote applications that belong to different organizations is called Electronic Data Interchange (EDI) (Pfeiffer 1992). EDI is used to implement inter-company computer-to-computer communication of Business Transactions in a standard format. American National Standards Institute (ANSI) X12 EDI transmission and control structure defines three levels of electronic envelopes known as Interchange, functional group, and transaction sets. UN/EDIFACT United Nations Electronic Data Interchange for Administration, Commerce, and Transport has also provided control features in the headers and trailers of its electronic envelopes that are interchange, functional group, and message (Marcella and Chan 1993). The cost of the systems needed along with the difficult format of the language and the need for training the personnel are some of the barriers to use EDI in different businesses.

ebXML (2001) Electronic Business using the XML. ebXML is a set of specifications that enable enterprises conduct electronic business over the Internet. ebXML defines a business transaction as an atomic unit of work in a trading arrangement between two business partners.

eCo Framework project (eCo 2002) focuses on demonstrating the value of the integration of three ecommerce services: semantic integration of multiple database types with multiple data constructs and data libraries, trusted open registries, and agent mediated buying. The eCo specification is a framework that allows organizations to discover each other on the Internet and determine how to conduct e-business operations with their business partners.
RosettaNet (2000) is an initiative with the aim of developing electronic business interfaces for the electronics industry. RosettaNet builds upon the Internet and XML to define three layers of standards: Partner Interface Processes (PIPs) that formalize the characteristics and requirements for specific transactions between parties; dictionaries that define the properties of the products, partners and business transactions; and implementation frameworks that specify data exchange implementation details. RosettaNet compares the human-to-human business exchange to the server-to-server e-business exchange. To build a transaction human use their sound and agree on an alphabet to create words. Then they apply grammatical rules to make a dialogue that is conducted through a telephone line to form a business process. The Internet enables a server-to-server business exchange. In an eBusiness transaction, XML works as the alphabet. The four components of the words, grammar, dialog, and the business process are the gap that RosettaNet is filling to conduct a standardized eCommerce application.

Many research projects have studied the communication of information in AEC/FM industry. For example, Khedro (1995) studied the use of distributed artificial intelligent techniques to facilitate design and construction integration through cooperative network communications; and Halfawy (1998) studied the agent-based integration of structural design/analysis and construction scheduling of bridge projects. But few studies have addressed the formalization and standardization of the transactions. In the AEC/FM industry, the data dictionaries have been defined by a number of data models, but the other levels of business exchange, specifically transactions and implementations, are still left for different organizations to agree upon in an ad hoc manner.

SPECIFICATIONS OF AEC/FM TRANSACTIONS: PROJECT OVERVIEW

A research project was recently launched with the goal to formalize, classify, and develop standard specifications for AEC/FM transactions. As part of the process to develop the transactions standards, common business transactions or scenarios are defined based on the IFC data model. The IFC data standard defines the “content” of a transaction, while the transaction standards define the “context” of the transaction. The objectives of this research can be summarized as follows:

*Analysis of transactions use in the industry*

- Trace the growth of the usage of the standards in the AEC/FM industry. A survey was conducted in this regard.
- Identify and utilize the result of similar efforts within other industries.
- Identify the major benefits of a standard language for data exchange in AEC/FM industry.
- Demonstrate the role of existing standards as the syntax and semantics of the standard language.

*Develop a framework for transaction standards in AEC/FM*

- Classify different transactions in the AEC/FM industry.
- Investigate specific issues surrounding the potential for transaction standards for AEC/FM
- Provide a standard template for transaction standards for AEC/FM.
Develop specific prototype transaction standards:
- Analyze a special process as it happens in the industry (as is).
- Identify a better, more effective way to do the same process (to be).
- Define transaction specifications for a particular topic area within AEC/FM.

Demonstrate the use of transaction standards in a prototype system:
- Create a prototype system that uses the transaction specifications to support a range of business transactions between various system components.

The content of the transaction specifications define the workflow models of various AEC/FM project processes, and the purpose and scope of each transaction. Specifically, it will describe the following:

1. Process Model/Data Flows: A flow diagram that uses UML Unified Modeling Language “swimlane” activity diagrams to demonstrate the sequences of document flows between participants, conditional logic, start/end/failure states, etc.
2. Data Content: Data contents of business documents, presented as a data model that will likely be drawn from existing data models (such as the IFCs), but is expressly presented in language appropriate to the data exchange domain. This data content model can then be mapped to specific data model standards such as the IFCs in the “Bindings” sections below.
3. Transaction Controls and Characteristics: The maximum time allowed to acknowledge receipt, the maximum time allowed acknowledging acceptance, maximum time allowed to perform a task, authorization requirements, etc.
4. Bindings to standard data models and implementation protocols: Maps the data model to one or more standard data models such as the IFCs, aecXML models, etc. and maps the business transaction to specific messaging implementation mechanism, such as BizTalk messaging.

CLASSIFICATION SYSTEM FOR AEC/FM TRANSACTIONS
Transactions happen in different stages of the project life cycle; each stage involves certain areas of processes that deal with special types of activities. A classification system is needed to categorize different transactions based on their information exchange semantics. At this stage of the project, we classify transactions based on the project stage at which they occur: namely: Business Planning, Pre-Design, Design, Contract Tender and Award, Construction and Contract Administration, Acceptance and Commissioning, and Operation and maintenance. This classification appears to be sufficient to categorize a large number of transactions. Furthermore, classifying the transactions based on the stage of the project would allow these transactions to differ according to the project stage at which they are happening. For example a submission of a change in the drawings is different in the construction stage than in the design stage. Not only the process of the submission is different, but also the information exchanged and liability issues are different. Another example is the bidding process, submission of a quote in the bidding process and the liability issues related to it is different than the submission of a quote in the design stage.
Every project stage consists of different areas of work. Transactions could be further classified based on the specific work areas they address. For example, the design stage consists of engineering design, cost estimating, and scheduling. The transactions related to each of these areas mainly address the exchange of product geometry, material quantity, specification, cost information, and project schedule.

A transactions classification system would allow the modeling of any type of data exchange that could happen in the course of AEC/FM projects. Project information is generally contained in a known set of documents. (Wix and Liebich 2000) classified project documents based on their category (archive, commercial, contractual, financial and technical) and type (approval, cost plan, external reference, list, mail, order, payment, schedule, coordination, etc.). Transactions could correspond to exchanging a specific document. Therefore, a number of standard transactions could be defined based on the specific type of documents involved. However, portions of information that are typically exchanged in a typical project may not correspond to any of the known types of documents, for example, a request to retrieve the product data for a specific group of building elements. Another aspect that the classification system would look at the different roles involved in the data exchange process. Since contracts define the responsibilities, authorities, and liability issues, so it is important to know who is the sender of the information and who is the receiver of the information.

SAMPLE SCENARIOS OF AEC/FM TRANSACTIONS

This section presents two examples of AEC/FM processes. The first example is the Document Review process that happens in many different stages and between different roles in AEC/FM industry. The second example is a materials delivery scenario where a scheduler, subcontractors, and suppliers exchange information to schedule materials delivery to the site.

DOCUMENT REVIEW TRANSACTIONS

The Review Process happens in many different stages and between different roles in AEC/FM industry. Typically, the manual exchange of documents during this process falls short in supporting the needs for timely checks and approvals in a concurrent environment. A document should be reviewed, checked, and commented. The document could be a drawing of a piece of equipment, a plan, it could be a change during the construction phase or a suggestion during the design phase. These comments or approvals might be sent to the owners from governmental bodies, to designers from regulatory authorities, to vendors from project managers, to service designers from the architects, and so on. The sender of the document has received or developed a document that needs to be checked. The review process has been chosen because of multiple use cases in the industry, it is obvious that when defining the specifications of the transactions involved in this process a special use case will be chosen.

The reviewer according to his/her knowledge, using some external codes, or policies might have produced some checklists or questionnaires to check the received documents. After comparing the document with the requirements, she/he makes comments and sends the comments to the sender of the document. Figure 1 shows the steps taken by the reviewer for the code checking activity based on providing a checklist or questionnaire, which is common for quality assurance purposes wherever applicable.
In practice these steps are time consuming and prone to human mistakes. By automating and standardizing the review process, many problems related to delays and legal discussions for the causes of delays could be solved. The finish to start relationships between activities that are in the as-is process should change to parallel relationships which could be possible by integration of code checking. Figures 2 and 3 show the transactions involved in the process of submitting documents and comments. These transactions could be used when a document is sent for information distribution, approval, comment, or as requested. Also the reviewer can send responses such as acceptance of the document content, revision request, reject the document, or just to confirm that the document has been reviewed with no comments if not needed.
For example, consider the following scenario. The architect has prepared some drawings that should be commented by different department experts. The drawing is sent as part of the transaction of “SubmitDocumentComment.” The owner is notified about this transaction. The architect sends it to other departments to request their input. Different departments based on their codes, knowledge, or policies to check the document and make their comments. Departments would respond to the architect with their comments which could be ReviseDocument, NoExceptionDocument, RejectDocument, or reviewedDocument. The architect would then review the comments. The process will be repeated until until every department sends a NoExceptionDocument. After receiving all of comments of acceptance, the architect would then send a ConfirmDocument transaction to the departments.

![Swimlane/sequence diagrams for the “SubmitDocumentComment”](image)

**MATERIAL DELIVERY TRANSACTIONS**

The scenario considers a concrete supplier (supplier A) who has to cancel the concrete delivery and therefore, sends a delivery cancellation notice to the subcontractor (Subcontractor 1), who, in turn, has to notify the general contractor’s scheduler. The scheduler accepts the cancellation and informs another subcontractor (Subcontractor 2) whose activity depends on the concrete delivery to cancel their material delivery. Subcontractor 2 sends a “DeliveryCancellationNotification” transaction to Supplier B, who responds with a “CancellationAcceptance” transaction. Subcontractor 1 will receive a “RequestDelivery” transaction to reschedule concrete delivery, and subsequently send another “RequestDelivery” transaction to the scheduler. The scheduler responds with a “DeliveryAcceptance” transaction to Subcontractor 1. Figure 4 shows the activity diagram for the “check schedule” process. The scheduler checks for available resources (labor and equipment) as well as the sequence of other related activities in order to make a decision to
accept or reject the delivery request transaction. Figures 5 and 6 show the transactions involved in this scenario.

CONCLUSIONS

In a typical project, information is represented in the form of unstructured documents that are exchanged in an informal and manual manner. Given the complexity and size of information and the number of participants in a typical project, the difficulty to formalize, structure, and organize project information flow becomes evident. Experience shows that a significant
amount of project time and resources are spent to access, search, and exchange information. Inefficient communication of information have often resulted in project cost and time overruns, reduced quality and productivity, rework, loss of design intent, and the inability to appropriately access and communicate project information in a timely fashion.

A methodology to develop transactions standard in the AEC/FM industry is presented. This standard will allow AEC/FM systems to exchange information in a consistent way and provide opportunities to improve information access and management across the industry.

![Swimlane/sequence diagrams for the request delivery transactions](image)

**ACKNOWLEDGEMENTS**

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**REFERENCES**

GRADUATE EDUCATION IN ENGINEERING MANAGEMENT: THE CONCURRENT APPROACH
A CASE STUDY

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ABSTRACT
The paradigm shift in concurrent engineering is that a multidisciplinary team of experts with different roles and perspectives performs the engineering and construction tasks. The interaction between team members will affect not only the characteristics of the product, but also the structure, norm and culture of the organization, having further influences on the engineering and construction process and further downstream on the final result.

The paper analyses the main obstacles that show up in the implementation of concurrent engineering in the construction industry. People issues are being emphasized. The authors suggest that personnel training in this area is a key factor in realizing the bottom line goals. Different training trends are being presented.

Offering “in-house” training towards a graduate degree is becoming a feasible concurrent solution. Financial and logistical support to such a program is to be provided by the organization. This solution will enable engineers to work full time and at the same time get their degree without having to give up their job. The advantages for the organizations offering convenient access to advanced education, is that this educational system can help them recruit top people, as well as motivate existing employees.

In 1995 the Department of Civil Engineering at University of Florida started a training program that is offered in the Army Corps of Engineers in the Jacksonville district. The paper will analyze the conclusions drawn from seven years of conducting this program and will discuss some problems that had to be overcome.

KEY WORDS
Concurrent Engineering, implementation, concurrent teams, delivering training.

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INTRODUCTION

The construction industry has been moving towards concurrent engineering (CE) for many years (Katranuschkov et al. 1996). Despite this tendency, the level of success achieved in practice through the application of concurrent engineering is still far away from the expectancies. The different levels of training and experience of the personnel involved in the construction business in combination with other organizational particularities have a limiting effect on the level of concurrency and collaboration of work to be achieved.

Concurrent engineering issues, such as the management of the process, product, documentation, and communication, are still being handled in a fragmented manner. But fragmentation creates professional dissonance and this is bad for innovation (Whyte and Edge 1999). Interoperable environments have yet to be developed which can fully integrate into practice and increase the uptake of concurrent engineering.

The paradigm shift in concurrent engineering is that a multidisciplinary team of experts with different roles and perspectives performs the engineering and construction tasks. Their role is to contribute to the tasks collaboratively by making decisions and sharing the information with each other. Dynamism is another characteristic of these “concurrent teams” as participants keep on evolving and continuously interacting during the holistic lifecycle of construction process. This interaction will affect not only the characteristics of the product, but also the structure, norm, and culture of the organization, having further influences on the engineering and construction process and further downstream on the final result.

One of the most important governmental organizations strongly committed to the implementation of concurrent engineering is the Army. In their mission to design, maintain, and rehabilitate the Army's infrastructure and to sustain installation environmental quality the Army Corps of Engineers is engaged in developing the techniques, strategies, and tools to provide Army planners, designers, construction managers, and facilities operations managers with the basis for better decision making. The efforts include the development and advancement of technologies from which concurrent engineering is one important area.

Personnel training in this area is a key factor in realizing the bottom line goals. Corporations have even established their own universities to provide company-specific training to their employees. Offering an “in-house” graduate degree is becoming a feasible concurrent solution referring to the fact that the students will have the potential of executing in parallel two different tasks: working full time and getting their degree without giving up their job. Financial and logistical support to such a program is to be provided by the organization. The advantages for the organizations offering convenient access to advanced education, is that this educational system can help them recruit top people, as well as motivate existing employees.

In 1995 the Department of Civil Engineering at University of Florida started a training program that is offered in the Army Corps of Engineers in the Jacksonville district. The program was using three different lecturing tools like: professors traveling to organization’s location to teach graduate classes there, graduate courses offered on videotape (FEEDS), and finally on-line courses (Internet).

The paper will analyze the conclusions drawn from seven years of conducting this program and will discuss some problems that had to be overcome. The authors believe that
such a program can be developed for almost any midsize to large organization. Steering the experience in outsourcing from this program will enable other universities to develop similar programs in their area.

IMPLEMENTING CONCURRENT ENGINEERING

The implementation of Concurrent Engineering addresses three main areas: people, process, and technology. It involves major organizational changes because it requires the integration of people, business methods, and technology and is dependent on cross-functional working and teamwork rather than the traditional hierarchical organization. From the problems encountered by companies in the process of introducing Concurrent Engineering, lack of training in the teamwork was often mentioned.

Participants in the panel discussion at the 2nd International Conference on Concurrent Engineering in Construction (CEC99) pointed out that CE is primarily about people and how to get them working synergistically. They supported the idea that overall the focus has to be on people as the main driving force of concurrent engineering initiatives. A primary need identified to contribute for a successful implementation of CE in construction is to eliminate the gap between industry and academia (CEC99). In order to build a bridge between the two parties a concurrent approach has to be taken: academia and industry should co-operate as an integrated multifunctional team.

One major obstacle to be noted in the interaction between academia and industry is that they both "speak a different language". In order to mutually identify, understand, and then solve the organizations' problems researchers should be invited to visit large organizations (CEC99). Smaller organizations might not formally require concurrent engineering, because they naturally operate in this form (Ainscough and Yazdani 2000). One of the reasons of poor academia-industry interaction lie in the fact that the industry fails to appreciate the applicability of the research findings of academia because they are not really addressing the issues and needs of the industry. A “customer focused” approach, where the customer is none other but the industry, is one of the solutions (CEC99).

CONCURRENT TEAMS

Concurrent engineering brings together multidisciplinary teams, that we would name “concurrent teams” (CT), in which product developers from different functions work together and in parallel from the start of a project with the intention of getting things right in a timely and efficient manner. Sometimes, only design engineers and production engineers are part of a CT. In other cases, the CT includes representatives from purchasing, marketing, production, quality assurance, the field and other functional groups are part of a CT. Sometimes customers and suppliers are also included in the team.

One of the greatest challenges in managing the simultaneous operation of inter-related tasks is to figure out ways that get people to work together as a team because human beings have a natural tendency to be territorial and are likely to attach top priority to personal interests (Prasad 1997). Creative win-win solutions have to be found in solving interpersonal and/or intergroup conflicts. Another important aspect is training CT’s on dealing with change during the entire life cycle of a product. Communication between team members should flow
freely, unrestricted by personal, physical or semantic barriers. Finally, success can be achieved only if the CT is customer focused.

DELINEIBING TRAINING

The growth of the Internet has created new avenues for training. Web-based technologies provide many benefits in delivering training and educational services, some of which include (a) relatively low cost, (b) real-time, and (c) ease of access to sources of knowledge. Many companies express their willingness to provide necessary infrastructure such as computers and Internet access so that their employees may receive training as needed and pursue the goal.

The change in the training environment, as well as the broad range of potential users of concurrent engineering techniques, requires a thorough analysis of the knowledge that will be required for intelligent and effective use of the new model. Identification of subject areas that will be need to be addressed and recommendations for implementation in training programs should be developed.

From the training trends discussed by education specialists the following are mentioned most often (Heathfield 2002):

1. Multimedia and on-line training. The American Society for Training and Development (ASTD) conference in Dallas noticed a proliferation of online providers of educational sessions. The current move in organizations has been to offer training on CDs, but the Web-based training (WBT) is not far behind. The quality of the courses varies as does the amount and type of multimedia used in their presentation.

2. Electronic Performance Support Systems (EPSS) are an additional topic generated by WBT. Dealing with the interface between people and software and creating and offering courses that trainees will actually finish are two main concerns. An attempt to move traditional manual-based courses online resulted in courses looking like training manuals online’ depleted of the Web advantages of interconnectivity and the ability to publish real-time, up-to-the-minute information. Integration of a real, live instructor and peer interaction with Web-based or CD training is still under discussion.

3. Performance consulting. Emphasis in training is now placed on providing a range of potential solutions that include in-depth needs assessment via interviews, surveys, and focus groups. Alternatives to training offered by progressive human resource departments include coaching, organizational development or planned change consultation and interventions, facilitated planning sessions, and large group processes. Training provided is custom-designed with stated outcomes congruent with the direction of the business.

4. Performance management. Integration of training and development into an entire performance management system is another trend. Organizations are moving away from the long-established one-on-one appraisal or performance review with a boss once per year. They are designing performance management systems that provide an individual with more frequent feedback from many points of view including peers, direct reporting, staff members, and the boss. The feedback, known as 360-degree feedback, provides a more balanced set of observations for the employee. The performance management
system also integrates a performance development plan for the individual designed to assist the employee to continue to develop his skills and abilities. For these plans, preference is accorded to integrated corporate university courses and internally custom designed and presented training. Performance development plans may include coursework, but also provide learning activities on the job such as special projects, serving on cross-functional teams, and skill stretching job assignments.

CASE STUDY

GENERAL INFORMATION

The University of Florida was approached by a major engineering organization, the Army Corps of Engineers, about the possibility of offering a master’s degree in construction/engineering management. This organization has in its Jacksonville district around 150 engineers, architects, and related professionals that would like to pursue their graduate degree. The Army Corps of Engineers made it clear that they would support the program but because of budget and manpower limitations their employees would not be able to travel to Gainesville where the University of Florida is located.

The army estimated that the cost of sending an employee for 18 months to the University in order to get a Master’s degree is close to $120,000. Because of those high expenses, the Army could send only one employee per year for full time studies. A preliminary survey showed that 30-40 Army engineers would like to participate in the program.

Trying to respond to the industry’s needs, the University of Florida has decided to offer a Master’s degree program in Jacksonville using distance education tools. The program developed at University of Florida was designed to satisfy user’s training needs.

PROGRAM

The Master’s degree currently offered to the Army Corps of Engineers is a regular Civil Engineering Master’s degree which includes 32 credit hours of which 12 credits have to be in the major area of engineering management. The rest of the credits can be from various areas of civil engineering and related management areas. All the students will have to submit a Master’s report before the completion of their studies. As of the end of 1997, twenty students participated in the program. The majority of them finished 50-70% of the required credits. Two students were able to complete their degree by coming to the University as full time students for a short period of time.

The second cycle of the Army employees pursuing their master’s degree started in 1978 and 10-15 new students joined the program. This experiment has gotten a very positive reputation around Florida, and other organizations like the Department of Transportation, public works organizations (Sarasota County) are trying to participate in similar programs.

CONCURRENT APPROACH

Students accomplished their tasks by working in concurrent teams that focused on various aspects of engineering design, production, and construction management. Appendix 1 and Appendix 2 offer an example of an in-class assignment and a term project assignment.
respectively, both designed to make students work in teams. Assignments were also designed specifically to develop in students the ability to acquire and interpret information, to manage information, to communicate information, to apply information to specific tasks and be innovative, and to apply all these competencies in a multi-disciplinary context. Working in teams required students to develop skills in group dynamics, compromise, debate, persuasion, organization, leadership, and management skills.

In this new CT approach, students had to explicitly communicate and think about sets of alternatives, which were finally narrowed, converging toward a single solution. The CT’s had to roughly explore the “design space”. The instructor defined a set of constraints in order to help the teams getting to a final solution. Teams were able also to identify intersection points between each other’s sets of alternatives and do benchmarking.

One of the primary issues was the formation of teams. Collaboration rather than individual effort was the standard, and team members realized that shared information is the key to success. Team members had to commit to working cross-functionally, be collaborative, and constantly think and learn. The role of the instructor was more as of a coach than a leader. He/she supplied the basic foundation and support for change rather than to tell the team members what to do. By chance team members had different educational backgrounds. Civil engineers, mechanical engineers, electrical engineers, and chemical engineers had to work together to complete a task. Instructors used this aspect to simulate the concurrent environment, and also to familiarize students with integrated teamwork.

**EDUCATIONAL TOOLS USED IN THE PROGRAM**

The following educational tools were used in the case study. Their advantages and disadvantages will be discussed in the following pages.

**DISTANCE TRAVELLING**

A few of the professors were ready to travel to Jacksonville in order to teach in-house graduate courses. The distance created some administrative problems, but with the use of e-mail, phone, and fax, most problems have been solved. This method was the best one regarding interaction between the professor and students. However, this method is very expensive and time consuming. Total cost of teaching 2-3 credit hours was $15,000, including lecturer’s fee (over the regular salary), travel, per diem and administrative cost. When the course was a required one, 25-30 students participated in the course and the cost per student was around $500/student per course, compared to regular fees at the University of Florida of $400/student. This difference was acceptable for the Army. However, when classes were elective, only 10-15 students participated and the cost per student was very high. The second problem was that most of the professors consider this method to be very exhausting (it is a full day of work) and only a few were ready to continue doing it.

Printed materials have been used extensively in this case because of the advantages they offer, like spontaneity, perception of being non-threatening, and the cost effectiveness. Disadvantages like outdated material and lack of timely feedback from the instructor can be solved easily by more advanced means of communication:
VIDEO COURSES
For many years, the University of Florida has offered courses that were taped in studios in Gainesville and the videos were sent by mail to various locations. Each student could watch the tape at home/work and participate in the class, homework were sent to the lecturer by mail, tests were done in-house with some security system.

This system is economical and very efficient. The cost for the students was like regular course tuition. Because of the extra efforts of the lecturer there has been university discussion to increase such course tuition by 25% and to give to the lecturer some monetary incentive. The major disadvantage of this method is not having any direct interaction between the professor and the students and both parties admit that this way of teaching is less beneficial than regular teaching.

VIDEOCONFERENCES
Videoconferencing offers the capability to broadcast audio and full-motion, to slow scan, and to freeze-frame images over a closed circuit to one or more locations. One of the advantages of videoconferencing is the visual connection established among the participants. Conversation and body language can be used to enhance communication. Some of the advantages of videoconferencing include that frequent interaction increases understanding, and the method involves convenient access to remote experts, besides, the preparation and training for this media is minimal. This method also offers document sharing for collaboration. The falling cost of equipment is contributing to the increased use of videoconferencing. A $50,000 mid-range rollabout video-conferencing system costs about $10,000 per year when depreciated over five years.

In this method the lecturer was teaching his regular courses for the full time students at Gainesville, however he was doing his lectures in the distance education studio. Using telephone connections his lecture was transferred to the Army studio in Jacksonville.

The Army studio included a few video monitors and video cameras. When any participant in Jacksonville had a question or a remark he/she called the studio in Gainesville establishing an audio-visual communication. There were some delays in communication time but after some early technical problems, the system was working very well. The major advantage with this method is the interaction between the professor and the students. In the future, this method will become the major tool for our distance education program. Economically, it is not expensive when using telephone lines. The cost of the 2 studios is substantial but it can be distributed over many courses and for many years. The major disadvantage of this tool is that the professors have to get used to the new media and they would need training and more time for preparation.

One of the major conclusions from using this method was to video tape the lecture at the source (university) and to send the tape (by fast mail) to the students in Jacksonville (they got it the next day). The tapes from the source were of a much better quality than the recording in the Jacksonville studio.

INTERNET COURSES
Internet is the largest and most powerful computer network in the world. It is used by more than 30 million people in more than fifty countries, and current estimates suggest that over
four million computers are part of the Internet (Kochmer 1991). Universities, schools, companies, and private citizens can have access to the Internet either through affiliations with regional not-for-profit networks or by subscribing to information services provided by for-profit companies. This new media has opened a large variety of possibilities for distance educators to overcome time and distance to reach students. Instructional possibilities of the Internet include electronic mail (e-mail), bulletin boards, and worldwide web (WWW).

A few professors are developing courses on Internet. This is in an experimental stage and the idea is that all the course material will be offered on the Internet. A recently developed course at University of Florida, using Internet WWW is “Basic Traffic Operations” (Figure 1). This method has many advantages if the right type of course is chosen. It will fit to those courses that are very defined and have few discussions. The authors’ opinion is that courses like cost estimate, scheduling, legal, and similar courses are suited to this media. The major disadvantage of Internet courses is that developing a good course of 2-3 credits takes substantial resources (time, money). From the authors’ experience it will take at least a year of hard work to develop a course using Internet.

![Figure 1: Course offered on Internet WWW at University of Florida](image)

**FEEDBACK**

The U.S. Army Corps of Engineers Jacksonville District's 232 person Engineering Division has a large, diversified and complex civil works program. Major engineering features in their $59 million program include flood control, navigation, beach erosion, concrete, rock and earth-fill dams, jetties, levees, dikes, bridges and environmental restoration engineering. The Division utilizes professionals with expertise in hydrology and hydraulics, soil engineering, geology, surveying and mapping, cost engineering, structural, mechanical, electrical, and
civil engineering and architecture. Approximately 50% of the Division’s work is accomplished by other Corps districts or private sector Architect Engineering firms operating under the direction of the Division's technical staff. State of the art computer equipment is used to develop complex models for conceptual planning, analysis, visualization and detailed design as befits a high technology modern engineering organization.

Management recognized that education is a critical variable for this professional engineer based organization. An assessment revealed the following:

- Lack of advanced degrees or course work by many of the current staff.
- Lack of graduate training opportunities in engineering and engineering management in the Jacksonville area.
- Concern over the expense of sending students out of the city for graduate courses.
- Unwillingness of the students to take all or most of their courses by video tape distance learning.
- Potential recruits increasingly expressing the desire to locate where they can continue their education.
- Existing staff’s strong desire for graduate training indicating such a program would serve as a retention tool.
- Recognition that many of the people that we deal with from outside the Corps have graduate degrees.

Management has a strong desire for the local courses to become part of a larger continuous learning initiative utilizing multiple forms of training. The University graduate courses offered both locally and by long distance complement training offered by the Corps and available short courses. These training opportunities are incorporated into a training plan for upgrading each individual's skills. Where possible the University Professors would spend periods of time working at the Corps. This has a dual benefit. It provides the Professor the opportunity to work on real world problems. It provides the student with an opportunity to interact with the Professor in applying higher level considerations to their regular problem solving.

Management is pleased with the graduate training that our people have received as well as the interest in all advanced training that this program has helped foster. We have had 4 students receive their Masters Degree and several others are moving in that direction. There is a high level of interest in all learning and we have had over 60 students explore participating in the after work graduate classes. After much effort by all, the in-house degree program has more than met our expectations.

CONCLUSIONS

Concurrent Engineering (CE) has become more and more an important paradigm in product development and also a widely accepted concept within the industrial and academic arena. The key to CE lies in concurrent exploitation of people, technology, processes, and products.
This is possible through cohesiveness and commitment by learning from and teaching others, and then taking several steps beyond in search of CE enlightenment.

Concurrent Engineering in construction will require true collaborative working between client representatives, construction professionals, suppliers and subcontractor organizations. The information technology required to facilitate such collaboration largely exists already. The barriers to the introduction of these technologies and efficient effective collaboration are human and organizational.

Training addressed at getting people to work together in teams plays an important role in the successful implementation of CE in construction. From the seven years of directing the training program at the Army Corps of Engineers the Jacksonville district the authors consider that overall the program is a success.

The authors concluded that training for concurrent engineering requires different media than conventional education does and it requires special training and specialization. Using a combination of educational/training tools is considered to be a good solution for concurrent training. Following the “concurrent way of thinking” both trainers and trainees should cooperate in establishing what tools to use.

REFERENCES


### APPENDIX 1

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<th>CORPS OF ENGINEERS</th>
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<td>SPRING TERM 2002</td>
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**IN-CLASS ASSIGNMENT**

Review the requirements of the Term project

In your teams, develop a plan for completing this assignment

The plan should include:

1. Selection of projects to be used
2. Major work items to complete the term project
3. Major milestones
4. Time for completing work items (schedule) and meeting milestones
5. Responsibility matrix for team member performance on work items
6. Contract agreement for team members that outlines
   - Team goals
   - Meeting times
   - Agendas
   - Meeting responsibilities
     - Note taking
     - Informing (contracting)
     - Action items
   - Rules for team members
     - Attendance
     - Notification
     - Conduct
     - Responsibilities/obligations
7. Consequences for non-performance team members

**DUE DATE: ________________________________**
APPENDIX 2

CORPS OF ENGINEERS
SPRING TERM 2002

TERM PROJECT ASSIGNMENT: Your term project requirements are as follows with adjustments to these requirements to be made by addendum:

PROJECT GOAL: To produce a project oriented manual

1. Each team is to select a project on which they will work
2. Chapter 1 - Create a flow chart showing the project organization that you will be using
3. Chapter 2 – Create a “line and staff” organizational chart
4. Chapter 3 – Create a schedule for the final program
5. Chapter 4 –
   a. Create an outline of the major work items for the projects
   b. Develop a CM proposal to the owner
   c. Develop a “procedural outline”
6. Chapter 5 – Develop a listing of the “Special Conditions” that would influence the project beyond that of ordinary specification requirements.
7. Chapter 6 – N/A
8. Chapter 7 –
   a. Refine your organizational chart to reflect the development of the project from 1 above until now
   b. Create additional organizational charts for:
      i. The project change process
      ii. The payment process
9. Chapter 8 –
   a. Refine the description of major work items to reflect any changes and to include budgeted cost
   b. Include a manual section on procedures for “cost control”
10. Chapter 9 – N/A
11. Chapter 10 – Create a project communications requirement and process flowchart for achieving your communication goals
12. Chapter 11 – Using reference such as “Means” create an estimate for the project based on your major work items (Compare with your original estimate)
13. Chapter 12 – Dr Herbsman will provide as an addendum
14. Chapter 13 – Create a work-breakdown structure for 3 of your major work items
15. Chapter 14 – For all of your major work items, create a procurement schedule
16. Chapter 15 – N/A
17. Chapter 16 – Develop an Outline for QA/QC program for this project
18. Chapter 17 – Create an organizational chart and plan for your project safety program
19. Chapter 18-19 – N/A
20. Chapter 20 – Create a flowchart on how to plan and handle dispute resolution on this project
ENCOURAGING CONCURRENT COLLABORATION IN MULTIDISCIPLINARY DESIGN PROJECTS: A CLASSROOM BASED STUDY

Lucio Soibelman\textsuperscript{1}, William O’Brien\textsuperscript{2}, and George Elvin\textsuperscript{3}

ABSTRACT

The rise of concurrent engineering in construction demands early team formation and constant communication throughout the project life cycle, but educational models in architecture, engineering and construction have been slow to adjust to this shift in project organization. Most students in these fields spend the majority of their college years working on individual projects that do not build teamwork or communication skills. Collaborative Design Processes (CDP) is a capstone design course where students from the University of Illinois at Urbana-Champaign and the University of Florida learn methods of collaborative design enhanced by the use of information technology. Students work in multidisciplinary teams to collaborate from remote locations via the Internet on the design of a facility. When we began the course, we expected that students would develop their group design projects by working together in an iterative manner, frequently exchanging information and ideas. In most cases, however, design iterations and information exchanges were much less frequent than we expected. This paper describes the goals, outcomes and significance of this new, interdisciplinary course for distributed AEC education. It presents its differences compared to other collaborative design courses and shares lessons learned and contributions. It specifically addresses methods for encouraging collaboration in a multidisciplinary design project.

KEYWORDS

Collaborative design, multidisciplinary design, concurrent engineering

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INTRODUCTION

Collaborative Design Processes (CDP) is a capstone design course where students from the University of Illinois at Urbana-Champaign and the University of Florida learn methods of collaborative design in the architectural, engineering and construction (AEC) industry enhanced by the use of information technology. Students work in multidisciplinary teams to collaborate from remote locations via the Internet on the design of a facility. Team members from structural engineering, architecture and construction management generate designs, schedules and budgets while experimenting with different work practices to take maximum advantage of information technology using commercially available software. Students also develop process designs for the integration of technology into the work of multidisciplinary design teams. The course is designed to provide students the experience, tools, and methods needed to improve design processes and better integrate the use of technology into AEC work practices. To-date, students have produced designs for a boathouse (2001) and a fitness center (2002) (Figure 1).

The course has several distinct features that set it apart from other collaborative courses. First, we use only information technologies that are readily available to most AEC firms, including Net Meeting, AutoCAD, Revit, and Bricsnet. The use of off-the-shelf software helps assure that the students will be able to apply their learning when they enter practice. Esoteric one-of-a-kind or extremely expensive programs may be of great experimental value in AEC education, but they leave the student without the possibility of actually using these tools in the average professional office. Second, over one-third of the course time is devoted to an intensive review and self-evaluation of the collaborative process employed by each team. After completing the facility design project, the students spend the final eight weeks of the course developing a detailed process critique in which they reflect on, evaluate, and suggest improvements to both the strategies and technological tools of their collaborative design process. These valuable lessons learned can then be shared and taken away by each student, improving future practice.

This paper describes the goals, outcomes and significance of this new, interdisciplinary course for distributed AEC education. It presents its differences compared to other
collaborative design courses and shares lessons learned and contributions. It specifically addresses methods for encouraging collaboration in a multidisciplinary design project.

**BACKGROUND**

Collaboration between geographically distributed parties is becoming standard practice in the AEC industry. The rise of design-build and fast track methods of project delivery demands early team formation and constant communication throughout the project life cycle, but educational models in architecture, engineering and construction have been slow to adjust to this rapid shift in project organization. Most students in these fields spend the majority of their college years working on individual projects that do not build teamwork or communication skills. When these students confront the intensively collaborative reality of today’s AEC practice the inadequacies of their education suddenly become clear. In fact, only 46% of all architecture alumni responding to a recent survey felt their school did a good job fostering their ability to work cooperatively in interdisciplinary teams (Boyer and Mitgang 1996).

The shift in project organization toward collaboration has been accompanied by dramatic changes in the media and methods of communication within the AEC industry. The intensive and rapid exchange of information engendered by design-build, fast track and other collaborative methods cannot be achieved using paper documents alone. Students in distributed, collaborative AEC courses today have the opportunity to experience a wide range of information technology tools capable of enhancing communication and collaboration, and graduates of these courses enter the industry prepared to not only participate in the teams that will shape tomorrow's buildings, but to lead them.

**UNIVERSITY OF ILLINOIS AT URBANA CHAMPAIGN AND UNIVERSITY OF FLORIDA CDP COURSE**

**COURSE OVERVIEW**

The CDP course is a capstone design course where students learn methods of collaborative design in the AEC industry enhanced by the use of Information Technology. Students work in multidisciplinary teams to collaborate from remote locations via the Internet on the design of a facility. Team members from structural engineering, architecture and construction management generate designs while experimenting with different work practices to take maximum advantage of information technology using commercially available software. Students also develop process designs for the integration of technology into the work of multidisciplinary design teams.

**COURSE MOTIVATION**

Facility design is fundamentally a collaborative, interdisciplinary, geographically distributed, multimedia activity. A typical AEC project, for example, might involve architects, a client team, structural engineers, mechanical engineers, electrical engineers, cost consultants, lawyers, interior designers, landscape architects, construction managers, construction contractor, subcontractors, materials suppliers, and various regulatory agencies. The various
individuals and firms that are involved constitute a virtual organization that exists throughout the life of the project and is then disbanded so that the components may be recombined for new projects. Coordination of the work of these parties to make a coherent design is a challenging problem. Too often, traditional practice has seen the development of designs that are over-cost, over-schedule, and of poor quality on several metrics (such as constructability, aesthetics, etc.).

Recent years have seen the advance of information technology to alleviate these problems. Today, it is possible for virtual design organizations to be supported by virtual design studios-networked facilities that provide the geographically distributed participants in a design project with access to the organization's databases and computational resources, efficient messaging and data exchange, and sophisticated video teleconferencing. Unfortunately, integration of this technology into the work practices of design professionals has been problematic. There is little evidence to suggest that this capability has significantly shortened facility design times or dramatically increased the number or quality of design alternatives. How to integrate information technology to improve the work practices of multidisciplinary design teams remains a fundamental problem. This course was designed to provide students the experience, tools, and methods needed to improve design processes and better integrate the use of technology into AEC work practices.

**COURSE OBJECTIVES**

1. Understand group dynamics and develop negotiation and decision making skills through direct experience of group design work and through critical reflection, evaluation and analysis of multi-disciplinary, net-based collaborative design process.
2. Complete facility designs including plan, schedule, budget, and structure using different work processes enabled by the use of information technology.
3. Learn how to evaluate and integrate technologies of multidisciplinary remote collaboration that will soon be the medium for design and delivery of AEC projects.
4. Design improved work process methods and make recommendations for the development of improved software tools for collaborative, multidisciplinary design.

**COURSE CONTENTS**

The course allows students to experience virtual design teamwork for themselves through hands-on design of a building project. This direct experimentation phase occupies one half of the students' coursework. A series of 12 lectures by faculty and industry experts from Architecture, Structural Engineering and Construction Management provide a framework for understanding concepts, issues and state-of-the art practice in collaborative design processes and technologies. Based on these lectures and discussions, students reflect on their own experience with the design project to produce a revised process to improve future collaborative efforts. There are two main assignments during the semester:

**DESIGN PROJECT:** Multidisciplinary groups of students are assembled with members from different schools. Each group has at least one structural engineering student, one project management student, and one architectural student. During the first half of the semester each
group works on the defined project with the goal of delivering the complete architectural design CAD files, the estimate, the schedule, and the structural project for the designed facility. To complete the project, a virtual jury is conducted.

PROCESS CRITIQUE: Students present lessons learned during the semester concerning the difficulties of collaborative design and propose process improvements. They critique their design process in the design project, including the difficulties of implementing the available IT tools to support multidisciplinary design. Based on their critique, students present improved work process methods, and make recommendations for the development of improved software tools for the design. The goal of the process critique is to help students understand the interaction between generation of information, modes of exchange, and the impact of new media for communication and accumulation of information mapping information bottlenecks and information overflows during the design process.

CDP AND OTHER UNIVERSITY BASED COLLABORATIVE DESIGN EFFORTS

A number of other courses were developed to teach multidisciplinary, geographically distributed teamwork. Fruchter (1999) developed a distributed learning environment that included six universities from Europe, Japan, and the United States and a tool kit that was aimed to assist team members and owners to capture and share knowledge and information related to a specific project, to navigate through the archived knowledge and information, and to evaluate and explain the product’s performance. Hussein and Peña-Mora (1999) created a framework for the development of distributed learning environments that was applied during a distributed engineering laboratory conducted jointly by MIT and by CICESE in Mexico. These authors studied students’ interaction within the distributed classroom and with the gained insights generated guidelines for the development of distributed collaborative learning courses. Devon et al (1998) developed a French-American collaborative design project using many different forms of information technology. Similar to the efforts described above several other universities developed their own collaborative design courses e.g., the University of Sydney (Simmoff and Maher 1997), Carnegie Mellon University (Fenves 1995), and Georgia Tech (Vanegas and Guzdial 1995), among others. These efforts were product centric with groups of students collaborating on a design project. The main objective of these classes was to support the students in improving the product being designed. The University of Illinois/University of Florida CDP course, in the other hand, was process centric providing the student with the tools to analyze and improve not just the designed facility but the design process.

During the CDP course after creating a design, schedule, budget and structural plan for a facility, students were asked to reflect on the group dynamics and technologies of collaboration they experienced. They were asked to propose improvements that may help future collaborators improve their design processes. They were expected to write a report with their perceptions of the team performance/dynamics and to develop process maps describing in a graphical language the flow of work in their team’s design process. In their report they were expected to specifically address the technological improvements which could facilitate collaborative design in the future.
RESULTS: PERSISTENCE OF “OVER-THE-WALL” METHODS

There are three primary work strategies available to a team with distributed members, each strategy reflecting a different relationship between tasks (Figure 2). First, teams may take a serial approach (top) in which each team member performs all of his or her tasks and then hands the results off to the next team member, the project being passed along from team member to team member until completed. This is the strategy we know as the “over-the-wall” method. Alternatively, they may perform their tasks concurrently, or in parallel (middle), each working on a separate task at the same time as the others, but without a frequent exchange of information. And finally, they may adopt an integrative or iterative approach (bottom), frequently exchanging information among team members performing separate tasks of short duration. When we began the course, we expected that students would develop their group projects by working together in an iterative manner, frequently exchanging information and ideas. In most cases, however, design iterations and information exchanges were much less frequent than we expected.

The advantages of integrative work methods have been confirmed in practice. They include improved process efficiency, accuracy, innovation and quality (Fergusson 1993). While the tools and training provided to students in Collaborative Design Processes give them the opportunity to rapidly exchange project information and iterate between tasks, most persist in taking an “over-the-wall” approach to developing their projects. Why?

Figure 2: Alternative approaches to collaborative work
First, design must be somewhat complete in order for the team to develop a schedule, budget and structural plan. Teams are made up of one designer, one cost estimator and one scheduler. In order to perform the tasks of cost estimating and scheduling, the team members responsible for those tasks must have a design on which to base their estimates. In all cases, the cost estimator and scheduler began the project by waiting for the architecture student to produce a design. The level of development of the design prior to input from other team members varied among teams, but in general, teams held off on exchanging information and ideas about conceptual designs longer than we expected. Second, while the information technologies available to the students made remote collaboration possible, available off-the-shelf technologies were not yet sophisticated enough to allow smooth synchronous collaboration such as marking up a design drawing simultaneously from remote locations. It is still much easier to work on one’s own tasks in isolation and then exchange “complete” information than to engage in the technologically and sociologically messy business of synchronous work or rapid exchange of “provisional” or incomplete work.

In addition, there is the matter of control. Students working alone on a task feel a high degree of control over task process and task results. But, when they release the results to others in an iterative exchange of information, the students no longer feel they are in control of their work. Students frequently expressed frustration when waiting for information from teammates, information that was needed in order for them to proceed with their own tasks. This frustration is felt in practice as well, as contractors cite waiting for design information as the most common cause of delay in building projects (Kumaraswamy and Chan 1998). Finally, the educational background of the students, whether in engineering or architecture, was not one that encouraged collaboration or built experience and skill in this method. Students tended to work alone in their university studies, and the few weeks of training in communication and collaboration that preceded the start of the design project in Collaborative Design Processes were not enough to overcome the mindset and habits of students accustomed to working on their own.

RECOMMENDATIONS

We believe collaboration with strong iteration and information exchange is desirable, given its favorable results in practice. What, then, are some of the incentives that could be introduced to encourage collaboration and iteration? One possible incentive is to introduce more milestones with specific deliverables along the way to the finished project. Desiring to keep the process as open as possible, we held just one interim meeting with each student team in which we played the role of the client, offering a “go” or “no go” on the conceptual design halfway through the project timeline. More reviews with specific deliverables aimed at encouraging or measuring collaboration could be employed. Another incentive would be to spend more time training the students in collaborative methods before they begin working together, and students frequently expressed their desire for more up-front training. However, we prefer to let the students learn about collaboration by doing it, rather than by listening to someone tell them about it. Their immersion in the collaborative design project is then followed by an intensive and critical self-analysis, the process critique, in which they learn from what they and their fellow students have done.
Another incentive to collaboration would be improved technological tools to facilitate synchronous group work and information exchange. The kit of tools currently available off-the-shelf make remote collaboration possible, but do not yet encourage synchronous collaboration. Two strategies are possible with respect to software for collaborative design – off-the-shelf or custom-built – and we chose to use off-the-shelf software. Given the intensive research and development on collaborative software taking place in private industry, these tools are rapidly improving and each new semester brings significant advances in collaborative software.

Students specifically cite waiting for information from their teammates as one of the primary frustrations of collaborative design. This leads to an additional incentive; information elicitation mechanisms could be introduced to encourage rapid response to requests for information. In the AEC industry, mechanisms aimed at enforcing rapid response in information exchange and decision making often involve economic incentives. In the classroom, we prefer to let the students define their own roles and responsibilities as they begin their collaborative project by drafting a team partnership agreement.

One incentive to collaboration spans beyond the scope of the individual course. That is to gradually reshape the curricula of architecture and engineering schools to encourage collaboration and exchange of ideas among students. If universities and schools can create an overall academic setting where collaborative, multidisciplinary work is considered commonplace, students could bring learned skills and experiences in collaboration to bear on a group design project, rather than learning these skills almost from scratch as they tackle the complexities of a large-scale design project.

In Collaborative Design Processes, our aim is to facilitate rather than impose frequent exchange of information and ideas. The partnership agreement drawn up by each team before they begin their collaborative project helps define some of the expectations and assumptions held by each team member. Project work then forces the students to confront the challenges of collaborative design directly. And the reflective process culminating in the group process critique gives the students the opportunity to analyze “what worked and what didn’t” in their work as a team. These three course components, together with some additional training in the tools and methods of group work up front, provide a setting that encourages students to learn about collaborative design and think critically about its challenges and opportunities.

CONCLUDING REMARKS

Overall reaction to the course by the students is very positive. For many of them, this is the first experience they have working in interdisciplinary teams. Other students with professional experience felt that the course was beneficial as they played different roles than they had in the past and that the chance to use new technologies was useful. Feedback at the conclusion of the class noted that the students enjoyed the hands-on aspects of the course and felt better prepared for practice after collaborating with people with different perspectives. Students also felt that they built some useful skills in both applying computer skills and in teamwork. Feedback from graduates of the class and now in practice generally supports these views. Some course graduates express frustration that they are unable to deploy in practice the tools they used in class (generally due to a lack of time and professional collaborators familiar with the tools).
The course also demonstrates that the existing state of computer tools enables effective work. In a short period of weeks, students go from a program assignment to generating a coordinated set of plans, schedules, and budgets. The students from Illinois and Florida do not meet face-to-face and do not have previous working relationships. We do not believe such rapid design development would be possible without the use of computer tools to mediate communication.

However, observation and feedback also indicates that the tools do not enable true collaboration. They are still most suited to over-the-wall type development. Tools do not provide effective capabilities to collaboratively explore in real time the different design alternatives along various axes related to the design, construction and engineering disciplines. That said, the use of Netmeeting and similar tools that allow desktop sharing and synchronous voice/video do provide a platform for real-time discussions. Most of the student comments about improving the tools related to enriching the Netmeeting whiteboard functions and/or better integrating this type of functionality with more sophisticated tools such as CAD.

The combination of instruction (lectures and discussions), action (collaborative design project), and reflection (group process critique), has proven an effective model for collaborative design education. It serves to introduce the students to many of the social, professional and technological challenges of remote collaboration currently facing the AEC industry. It highlights the importance of variations in experience, outlook and expectations among students from different disciplines, and the need to address these differences if a successful process and product are to be achieved. In this capacity, the course offers an important addition to traditional, discipline-specific curricula.

In the future, we will seek out new tools for collaborative design that allow for greater co-labor – simultaneous manipulation of design documents by team members at remote locations, for example. Currently, too many off-the-shelf applications for internet-based collaboration simply reinforce the accepted over-the-wall method of sequential, rather than synchronous, labor. The internet has the potential to change the nature of how we work together, and while specific tools and technologies seem to change almost overnight, we believe we have succeeded in creating at least the beginnings of a model that inspires students to ask “what if?” with regard to technology, collaboration, and the design process itself.

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REFERENCES


Ferguson, K.J. (1993). Impact of Integration on Industrial Facility Quality. 84, Center for Integrated Facility Engineering, Stanford University, Palo Alto, CA.


IMPLEMENTING IFC-BASED DATA MANAGEMENT SYSTEM FOR CONCURRENT AEC/FM PROJECTS

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ABSTRACT

Current practices and integration trends in the AEC/FM industry are increasing the demands for the implementation and deployment of concurrent project systems. This paper discusses the computational requirements and an approach to develop concurrent project systems that would potentially streamline and closely integrate various processes throughout the project life cycle. The approach employs the Industry Foundation Classes (IFC) to enable the interoperation of function-specific software tools through the use of a centralized integrated project model. The approach emphasizes modeling the multi-disciplinary aspects of the projects and linking inter-dependent parts of project information. A framework and a prototype system based on the proposed approach are also presented. The prototype system has demonstrated the utility of the approach and its potential to support the implementation of concurrent project systems.

KEY WORDS

Concurrent engineering, concurrent project systems, Industry Foundation Classes

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INTRODUCTION

Architecture, Engineering, Construction, and Facilities Management (AEC/FM) projects are typically accomplished by a collaborative multi-disciplinary effort of several organizations. Fragmentation of the industry has caused many problems that could be primarily attributed to the “gaps” between the design, construction, and facilities management phases of a project. Project information typically flows from design to construction to facility management, with very costly and time-consuming feedback loops in the form of change orders during the construction phase, or excessive maintenance work during the facility management phase. Project gaps have often resulted in project cost and time overruns, reduced quality and maintainability, loss of design intent, and the inability to appropriately access and communicate project information in a timely fashion. More frequently, this has resulted in contractual disputes, claims, and litigation, and sometimes in failures and life loss.

Project gaps have been primarily created as a result of the sequential nature of the projects processes and the isolation of upstream activities from any input from downstream project aspects. A study reported in (Hisatomi and Reismann 1994) concluded that 73% of the constructibility savings could be obtained when 20% of engineering was complete; and 91% of the savings can be obtained when 50% of engineering was complete. The study also showed that the largest savings were resulting from construction input into the design process. The International Association for Bridge and Structural Engineering (IABSE) has conducted another study that showed that “The average cost of rework on industrial projects exceeds 12%. Therefore, for the $140 billion US construction industry, this means a waste in excess of $17 billion annually. Design deviations (i.e. changes, errors, and omissions) accounted for roughly 80% of the increased costs, while construction deviations accounted for about 20%” (Hisatomi and Reismann 1994). A third study conducted by the Construction Industry Institute (CII) was also reported. That study has identified ten input factors as having the greatest effect on design efficiency. “Construction input to the design process” is one of these.

The need for project integration and closing the gaps between project processes is recognized as a necessity to achieve time and cost savings and to improve the overall projects quality. Experience with the project gaps and the demand to achieve close integration of project processes have created an increasing trend to adopt integrated approaches for AEC/FM projects, most notable is the use of design-build and partnering. Moreover, to cope with today’s competitive global marketplace, many AEC/FM firms are re-engineering their processes, forming partnerships, and outsourcing services in an effort to reduce projects time and cost, and to optimize the use of their resources. Integration trends in the industry are expected to become even more pervasive in the near future.

It is widely recognized that adopting a Concurrent Engineering approach to AEC/FM projects would potentially alleviate many of the problems associated with the project gaps and would lead to improving the projects quality while reducing their time and cost. Integration trends have created a strong demand for the deployment of concurrent engineering concepts. In essence, the concurrent engineering approach emphasizes addressing various project life cycle issues, including construction and facilities management aspects, at early design stages, allowing the execution of many such activities
simultaneously, and allowing information to efficiently flow between across project disciplines (Halfawy 1998). In addition to reducing the project time and cost, and supporting a team-oriented collaborative approach, concurrent engineering would also result in less change orders and re-work during the construction phase, and more efficient maintenance and management operations throughout the life of the facility.

However, project managers who have been involved in concurrent or integrated projects such as fast-track or design-build, would appreciate the complexity of coordinating tens of project processes and managing a tremendous volume of project information. Contractual and liability issues would further complicate the process of managing integrated projects. In a previous research (Halfawy 1998), we conducted field studies in a number of design and construction organizations to assess the impact and determine the requirements of implementing a concurrent engineering approach to AEC projects. Although many of the engineers and project managers we interviewed strongly supported adopting a concurrent engineering approach, some of them voiced concerns about the complexity that the integration would create and pointed out that, due to this complexity, concurrent engineering may never be widely adopted in the AEC industry. Many also noted that concurrent engineering may only be appropriate for large companies that offer both design and construction services or for large design-build projects. Although the arguments against concurrent AEC projects have some valid points, we believe that successful implementation and deployment of computational tools that address the complexities inherent in these projects would encourage the industry to accept and adopt a concurrent engineering approach. Without sufficient computational support, most organizations might prefer to limit the scope of their work, and in turn limit their liability, which in the long run would result in more fragmentation in the industry and more gaps between project processes.

In this paper, we present an approach to support the implementation of concurrent AEC/FM project systems. The approach aims to support efficient sharing and management of multi-disciplinary project information, and to enable the integration and interoperation of legacy software applications through developing and maintaining an integrated project model. A prototype system based on the proposed approach is also presented.

REQUIREMENTS OF CONCURRENT PROJECT SYSTEMS

The number and complexity of AEC/FM project processes and their associated information would require extensive computational support to manage project information and processes across various project aspects. Concurrent project systems would need to support a wide range of requirements, most important are: (1) supporting the integration of various project processes and enabling efficient information flow between these processes; (2) modeling, sharing, and management of project information across all project disciplines and throughout the project life cycle; (3) interoperation and data exchange between seamlessly integrated function-specific software tools; (4) modeling, management, and coordination of project workflow; and (5) collaboration of project teams. Satisfying each of these requirements represents a major challenge that needs to be addressed.

Traditionally, concurrent engineering applications focused on the design aspect by enabling feedback from downstream project activities to be included into the design process. However, a more comprehensive approach to AEC/FM projects would address the entire
multi-disciplinary scope of project activities and facilitate the information flow between various project processes including design activities (e.g., architectural, HVAC, structural), construction and project management processes (e.g., concurrent scheduling and estimating, constructibility review, site planning), as well as facilities management processes (e.g., maintenance, life cycle cost analysis).

AEC/FM projects involve the generation and manipulation of dynamic and large data sets with complex interrelated objects. Due to the evolutionary and iterative nature of project processes, a concurrent project system should enable users to define objects at multiple levels of abstractions and enable managing changes and versioning of these objects. The system should also maintain the consistency and integrity of project data, enable sharing of project information, and enable the interoperability of various software tools employed to support individual project tasks.

Most of the existing computational tools have been developed to function as stand-alone systems to aid in performing individual project tasks. A concurrent project system should support the integration of legacy software tools, and support interoperability and efficient data exchange among different tools through the use of standard data models.

Project activities typically require extensive computational support to be efficiently performed. Requirements of software tools, and their functionality at each stage of the project need to be identified. Tools need to support model-based approaches and provide flexible mechanisms to access their internal data models through standard interfaces. Tools performance and usability improvement is also a major challenge.

AEC/FM projects involve a large number of highly inter-dependent activities that need to be managed and coordinated efficiently. A concurrent project system should assist in identifying the dependencies and inter-relationships between project activities and enable the efficient flow of information among various project activities.

Project teams need to communicate to coordinate their tasks, exchange project information, provide feedback to related project activities, and to evaluate the impact of various decisions. Coordination of the project activities depends primarily on the ability to distribute and exchange information among project parties in a consistent and timely manner. Team collaboration involves the communication of different forms of data (textual, graphical) and different interaction modes (synchronous, asynchronous).

INTEROPERABILITY USING THE INDUSTRY FOUNDATION CLASSES (IFC)

Much of the research throughout the last decade was driven by the need to develop standard industry-wide data models for AEC/FM projects (Eastman 1999). These models are widely recognized as the main enabling technology to implement concurrent project systems. Most notable of these models is the Industry Foundation Classes (IFC), developed by the International Alliance of Interoperability (IAI) (IAI 2002). IFC is considered to be a mature and comprehensive model that is widely supported and accepted by the industry. The IFC model is based on the ISO 10303 Standard for the Exchange of Product Model Data (STEP). The IFC model was initiated in 1994 and has undergone four major releases. Many commercial software tools, such as Autodesk's Architectural Desktop, Graphisoft’s Archicad, Nemetschek’s Allplan, Microsoft's Visio, and Timberline Precision Estimator, have already implemented IFC file exchange capabilities.
The IFC model defines an integrated schema that represents the structure and organization of project data to support interoperability among various software tools. The model provides an abstract and conceptual representation of the project data in the form of a class hierarchy of AEC/FM objects. It defines the main data objects, their characteristics, and their inter-relationships. The IFC class hierarchy covers the core project information such as building elements, the geometry and material properties of building products, project costs, schedules, and organizations. Work is ongoing to extend the model to other project domains. In general, the information from many types of computer application that works with structured data about AEC/FM building projects can be mapped into IFC data files. In this way, IFC provides a standard data model and a neutral file format that would enable function-specific applications to efficiently share and exchange project information.

The IFC model architecture employs a layered approach to provide a modular structure of the model components (Wix and Liebich 1997). Four layers have been defined: a resource layer that describes distinct underlying concepts (e.g., geometry, units and measures); a core layer that defines a kernel meta-model and core extensions to define the basic AEC/FM objects (e.g., projects, products, processes, resources); an interoperability layer that defines data that is used across multiple domain areas (e.g., building elements, structural components); and a domain layer that defines detailed data used within specific application areas (e.g., space layout, power and lighting system design, property management).

Instances of the IFC are initialized, linked, and assembled by application software to create an object model of the building project (Foese and Yu 1999). In the simplest form of interoperability, the project model is communicated from one software package to another in a data file (e.g., using ISO 10303 Part 21 format). Upon receipt of the data file, the software will re-create the project model for further processing. As an example of the current capabilities of IFC-based file exchange, the following scenario has been implemented using tools developed by the Building Lifecycle Interoperable Software group (BLIS 2002).

- One tool can be used to define the basic rooms and spaces required for a building, including the names, areas, and other basic requirements. The resulting preliminary space plan can be exported to an IFC data file.

- The IFC file can be read into a two-dimensional technical drawing tool. In this tool, previously identified rooms can be arranged into an overall floor plan, and various design details such as windows, doors, plumbing and mechanical systems, etc. can be added. Again, the resulting design can be exported as an IFC file.

- The IFC file can be opened by an energy analysis tool constructed on top of a 3-D CAD package. Although the information had previously been constructed in a 2D drawing package, all of the elements had height and elevation properties, and they can form full 3-D models in the CAD system. This tool performs energy simulations on the resulting model, and allows design revisions to the HVAC components in the model, with the results again exported to an IFC file.

- The IFC file can be opened in a tool that generates a 3-D virtual reality view of the project, allowing the user to rotate, zoom in and out, and “walk-through” the building. This tool then runs a series of design checks; rules which look for
specific code conformance issues. Items that fail to pass the design checks, such as a room with insufficient fire egress provisions, will be highlighted in the 3-D model.

- The IFC file can be opened in a tool that itemizes all of the physical components in the building, and maps their properties to an estimating database, to build up a complete cost estimate for the project.

This scenario describes the current state-of-the-art in IFC-based information integration. Although much of the initial focus of the IFC has been on representing the physical components of buildings (i.e. the product models), the scope of the IFC also includes non-physical project data such as documents, costs, organizational aspects, schedules, construction resources, and other types of project information. In this work, we try to fully utilize the IFC modeling capability in all project domains, and to extend its scope to other project areas that are not yet supported (e.g., specifications).

**IFC-BASED APPROACH FOR IMPLEMENTING CONCURRENT PROJECT SYSTEMS**

Probably the most important requirement of a concurrent project system is to build and maintain a project database that integrates and supports the multi-disciplinary aspects of the project. This database would ensure the consistency and integrity of project data, enable efficient data sharing and exchange, support tools interoperability, and enable team collaboration and timely access to project information. The database would also allow downstream project activities to access the design information to evaluate and assess the impact of design decisions from the perspective of downstream project activities.

The IFC explicitly model a variety of project information beyond the facility physical products. However, the vast majority of existing IFC implementations imports the building product information, and use the product model to generate some other project information (e.g., bill of material), but they do not record the additional project information back into the IFC files to be available for other applications. As a result, the project management classes of the IFC schema remain almost entirely untested. Despite the fact that the project information in IFC files are based on a standard schema, this approach does not differ much from the traditional sequential approach where design data files are exchanged using other neutral file formats. In both cases, design data flows in a uni-directional manner. A concurrent engineering approach should support the project information to flow across all project processes and throughout the project life cycle.

Current scope of the IFC model does not cover some of the critical project processes such as specifications, structural design, site modeling and planning, and facilities management. Since an integrated project system would require modeling of data related to these project aspects, the proposed approach tries to extend the IFC model to address the unsupported areas, and to enable linking inter-dependent parts of project information into an integrated data model that can be accessed by all project processes.

The IFC define a flexible and powerful mechanism to allow extending the model through the use of the IfcPropertySet entity. An IFC property set could be used to define a set of properties (IfcProperty entities or other nested IfcPropertySet entities). A property set can be linked to any number of IFC objects using the IfcRelAssignsProperties entity. Using this
approach, we could, for example, define a property set that describes the specifications of a building element and link this set to the IfcProduct entity that represents this building element using an IfcRelAssignsProperties entity. Similarly, information that support cost estimating, construction planning, or facilities management could be linked to the facility IFC objects.

In addition to its extensibility, the IFC model also enables linking a wide range of project information, represented as IfcObject entities, through the use of IfcRelationship-derived entities. IFC uses objectified relationships to describe association among various objects in the model. For example, the IfcRelProcessOperatesOn entity could be used to link construction activities to the facility products that they operate on. Also, an IfcRelSequence entity could be used to specify the precedence relationship between two project activities.

The IFC mechanisms to link multi-disciplinary project information and to extend the data model beyond its defined scope makes it an ideal data model to support the implementation of concurrent project systems. In our proposed approach, we have used the IFC schema to incrementally develop a centralized integrated project data model that enables the interoperation of various function-specific tools and the exchange of project information among different project disciplines. Figure 1 describes the information flow in this approach.

A typical project would start by a small set of conceptual design entities that can be used to exchange the design information with a wide range of function-specific software tools that span different project disciplines. As a result of incremental generation and linking of project information, an integrated “project model” would be evolved. This integrated project model would represent a comprehensive view of the project and would become the glue that binds together various project aspects. The model would support multi-disciplinary project perspectives and maintain the relationships among various project entities. In fact, the ability to develop and maintain the integrated project model can be considered as the cornerstone to successfully implement concurrent project systems that can integrate multi-disciplinary project aspects and enable project teams to assess interactions and dependencies between various project activities.

![Figure 1: IFC-Based Approach to Implement Concurrent Project Systems](image1)

![Figure 2: Spiral Model of Information Growth of Evolving Project Processes](image2)
Given the evolutionary nature of the project processes (i.e., evolving from conceptual to preliminary to detailed stages), the integrated project model will evolve and grow as the project progresses. The evolution of the project processes and the growth of project information can be depicted using a spiral model (Figure 2). The central axis in the model represents the project model which starts from a simple conceptual product model and evolves into a more comprehensive and detailed project model as more iterations are performed over the life cycle of the project. Each project activity generates more information in a particular aspect and links this information back to the IFC project model. Currently, we are developing a method to enable managing evolving IFC products. The basic approach involves using property sets and a labeling scheme to identify IFC products as as-designed, as-changed, or as-built, and to track the history of changes in each modified object. Objects labeled “as-changed” would define a version number along with change information, and a reference to the original object. After the design and construction phases conclude, all products will be labeled “as-built.” A facilities management tool could then be used to create an asset inventory and prepare the FM database based on the information of the as-built products.

The following scenario illustrates a typical use of the integrated project model. Suppose that a preliminary architectural design is developed and a number of IFC design entities are defined. The design software generates an IFC model and exports the design data into a standard IFC STEP part 21 file or saves this data into a centralized project database that is maintained by the concurrent project system. Cost estimating, scheduling, and specification writing software import the design data, generate more IFC-based project information, and link this information together as well as with the project model that was initially used. Project participants from different disciplines could access the IFC project description and view data in their respective domains and any other dependent or related data in other domains. As project team members modify their portions of the project data, the concurrent project system would ensure the consistency and integrity of the project model through the use of integrity constraints as well as by tracking the globally unique identifiers (GUIDs) of the IFC objects. By recognizing the relationships between various project entities, the system could also implement methods to ensure that the project data are consistent or to determine whether any interdependent objects need to be updated. These methods could range from simple techniques to notify parties that might be affected by a change, to more sophisticated techniques to automate change propagation and conflict detection/resolution mechanisms. Multi-disciplinary project teams could also use the integrated project model to assess dependencies and interactions between different project aspects and to collaborate to evaluate decisions, resolve conflicts, and to plan actions. Clearly, this scenario would have significant implications regarding how a concurrent project system would support an integrated and multi-disciplinary approach to AEC/FM projects.

**PROTOTYPE IFC-BASED CONCURRENT PROJECT SYSTEM**

A framework for concurrent project systems that employs the proposed IFC-based approach was developed (Halfawy and Froese 2002). The framework defined a three-tier component-based tools-independent architecture and implemented mechanisms to enable efficient information sharing and exchange between various project processes. The component-based
architecture has several advantages over other approaches: systems will be highly maintainable and can be easily upgraded or extended since changes to any of the system components will have little impact on the rest of the framework; replacing or upgrading function-specific tools would have little impact on the framework; the components can be reused to support the development of specialized integrated project systems that address a particular class of facilities or projects; the components and applications could be transparently running in a distributed environment. The flexibility and modularity inherent in this architecture would result in more efficient implementation and maintenance of concurrent project systems.

The framework’s three tiers include: the applications tier, the concurrent engineering services tier, and the project data repository tier. The applications tier integrates a set of function-specific software tools. The tools integrated into the prototype have been selected to support architectural design (Architectural Desktop), construction scheduling (Microsoft Project), and cost estimating (Timberline Precision Estimating). Other tools are developed to support specification writing, construction progress simulation, and facilities management. Applications interoperate and share project information through the use of the integrated project data model. Applications could be specifically developed to support the IFC-based project model. These applications could be integrated into the framework without the need to use adapters. Legacy applications, however, would require the use of adapters to map their internal representation of the project data to and from the standard IFC schema. The implementation detail (e.g., language, methodology) of the adapter would depend on the specific Application Programming Interface (API) provided by the application as well as on the data-mapping interfaces exposed by the framework data management components.

The concurrent engineering services tier includes several packages, each implementing a set of reusable components to support a class of domain services (e.g., data management, workflow management, team collaboration, document management). Many technologies are currently available for developing binary-interoperable software components. Examples include CORBA, COM/DCOM, .NET, and JavaBeans. In our particular implementation, we based our prototype on technologies that are widely available in the AEC/FM industry in order to reduce the development and deployment costs of such systems. We implemented a set of data management components using the Microsoft COM/DCOM technology. The components are programmed using Visual C++ and Visual Basic languages. The prototype currently supports data sharing and tools interoperability in the form of file exchange.

The primary function of the data management components is to develop and maintain the IFC project database. These components are used by the rest of the framework to interface with the project data repository that contains the persistent IFC project objects. Figure 3 shows a sample project and its associated multi-disciplinary data in the prototype system. Ideally, the repository would be implemented on top of an object-oriented database management system so that services such as concurrency control, versioning, and transaction management would be easily supported. However, a simple file-based approach would be sufficient to demonstrate the key features of the IFC-based approach.

Framework applications can import/export project data using the standard IFC data model schema. Documents could be formatted either as STEP Part 21 Physical Files (SPF) or as XML files using BLIS ifcXML schema (BLIS 2002). The data management components enable mapping of project information from one view (or discipline) to another and hence
allow the exchange of project information between multi-disciplinary project team members. The data management components also support accessing a wide range of generic data sources such as relational database management systems (through the use of the standard ODBC interface) or XML files (using the XML DOM interface). The components support transparent access to local or remote data sources.

Since the framework components are developed using COM technology, adapters could access the interfaces of these components, which are published through the type library of each component. For example, the Architectural Desktop adapter, shown in Figure 3, accesses the data management components after importing their type libraries.

Figure 3: Multi-disciplinary Project Views of the Integrated IFC Project Model

Users may import an IFC file and map the IFC objects to corresponding ADT entities. The framework enables users to manage and navigate through project information through a tree-like “project explorer” interface. This interface accesses the services provided by the data
management components to provide a hierarchical view of various pieces of project information such as the facility product model, resources, schedule, cost estimate, specifications, and documents. Users could also associate pieces of information between different views to indicate “relationships” between different project elements. The project explorer enables users to link objects by a simple drag-and-drop operation. For example, dragging an activity from the construction schedule and dropping it onto a building element would automatically create an IfcRelProcessOperatesOn entity that associates the activity with the building element. The system uses this association information to generate a visual simulation of the progress of the construction process.

CONCLUSIONS AND FUTURE DIRECTIONS

Current practices and integration trends in the AEC/FM industry are increasing the demands for the implementation and deployment of concurrent project systems. This paper presented an IFC-based approach for implementing concurrent project systems. The paper also presented a prototype data integration and management system that demonstrated the utility of the approach and its potential to provide a useful framework for implementing fully integrated concurrent AEC/FM project systems.

With the basic product modeling capabilities of IFC now reaching a high level of maturity and beginning to reach the commercial marketplace, we are focusing our research on addressing the current limitations of the IFC model and developing ways to extend the model intelligence, data exchange mechanisms, project areas, and application domains. Specifically, we are working to extend the model in the following main directions:

- Moving beyond file-based data exchange. Current implementations of IFC-based integration rely almost exclusively on the exchange of IFC files. This simple mode of transferring data is very limited in its ability to manage shared and evolving project information that is accessed concurrently by many users, or to enable transactional forms of data exchange between project parties and applications. The development of IFC-based centralized object-oriented project repositories that support distributed and concurrent data access and management is the next logical step.

- Extending the IFC model to address project areas that are currently not supported. This could be achieved either by referencing and linking with other data modeling schemas (e.g., CIMSteel for structural design), by adding new property sets (e.g., to model specifications), or by introducing new IFC entities (e.g., facilities management).

- Extending the IFC model to enable modeling and managing the evolution and changes of AEC objects throughout the project life cycle. We are investigating adding new IFC classes to add support for modeling smart AEC objects that could enable the encapsulation of objects intelligence and knowledge into the model, and the representation of objects’ behavior, design rules, constraints, and procedures.
• Moving beyond ad-hoc transactions. While the IFC model standardizes the information content of an information exchange transaction, it offers no guidance to the context of these transactions. It is still left up to the parties exchanging information to come up with ad-hoc agreements about what data are being exchanged, for what business purpose, with what constraints and obligations on each participant, etc. We are pursuing the formalization and possible standardization of data exchange protocols to support IFC-based transactions in distributed and heterogeneous environments.

• Extending the IFC application domains. The IFC model specifically addresses building construction projects. Yet much of the content of the model is fairly generic and could be applied to other segments of the industry (e.g., bridges).

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REFERENCES


ONTOLOGY MAPPING BETWEEN PSL AND XML-BASED STANDARDS FOR PROJECT SCHEDULING

Jinxing Cheng¹, Pooja Trivedi² and Kincho H. Law³

ABSTRACT
Many ontology standards, such as STEP, ifcXML, aecXML and PSL, have been proposed for the A/E/C industries. Different ontologies exist and they have many advantages for information exchange within specific domain applications. However, the existence of different ontologies may cause many interoperability issues. For example, while PSL, ifcXML and aecXML all have provisions related to project management and scheduling information, an aecXML-compatible or ifcXML-compatible application cannot directly exchange information with a PSL-compatible application. In this paper, we address this information exchange problem by building translators among PSL, ifcXML and aecXML in the project scheduling domain. We examine the ontology mapping among PSL, ifcXML and aecXML, and compare their expressive power. Using the parsers and translators developed, we successfully demonstrate the information exchange among PSL, ifcXML and aecXML for various projects.

KEY WORDS
Process Specification Language, PSL, aecXML, ifcXML, ontology, information exchange

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INTRODUCTION
Ontology standards play an important role to support interoperability among applications. For the last two decades, there have been many ontology standards proposed and adopted by various industries. In this paper we examine the interoperability issues between Process Specification Language (PSL) (Schlenoff et al. 2000) and XML-based standards, such as ifcXML (Liebich 2001) and aecXML (IAI 2002), for the project scheduling task. Both PSL and XML-based standards have ontologies defined for project management and scheduling applications.

The different ontology standards provide users various choices according to their specific needs. However, the different standards may hinder interoperability since different applications may opt to adopt different ontology standards. For example, an ifcXML-compatible or aecXML-compatible application cannot directly exchange information with a PSL-compatible application. To address this problem, we evaluate PSL, ifcXML and aecXML focusing on ontology mapping between these standards for project scheduling applications.

INTRODUCTION TO PSL
Process Specification Language (PSL) was initiated by NIST (National Institute of Standards and Technology) and is emerging as an international standard for the manufacturing industry. The goal of PSL is to create a process interchange language, which could be used to exchange process information among different applications. PSL is based on first order logic and situation calculus. PSL ontology includes a central core, an outer core and a set of extensions. The PSL core consists of object, activity, activity occurrence and timepoint as the primitive classes. The PSL outer core includes a small set of extensions, which are generic and pervasive in their applicability, such as subactivity extension, activity occurrence extension and states extension. The PSL extensions include a set of ontology modules motivated by different manufacturing applications.

PSL is based on a formal language KIF (Knowledge Interchange Format), which is a language designed for use in the interchange of knowledge among disparate computer systems (Genesereth and Fikes 1992). KIF supports declarative semantics, and is logically comprehensive. When combined with domain specific ontology, KIF is a powerful knowledge representation language.

A PSL file consists of a set of logic sentences. The following shows examples of PSL sentences:

\[
(\text{occurrence-of occl a1})
\]

\[
(\text{before t1 t2})
\]

\[
(\text{subactivity-occurrence occl occ2})
\]

The first sentence \((\text{occurrence-of occl a1})\) means that activity occurrence \(occl\) is a particular instance or occurrence of an activity \(a1\). In the second sentence, two time points \(t1\) and \(t2\) are ordered, where \(t1\) is less than \(t2\). The third sentence specifies that an activity occurrence \(occl\) is a subactivity occurrence of an activity occurrence \(occ2\).
INTRODUCTION TO IFXML AND AECXML

XML (Extended Markup Language) is a meta-markup language that consists of a set of rules for creating semantic tags used to describe data (Young 2001). XML provides a mechanism to describe an object as a hierarchy of elements. Due to the popularity of XML, many efforts have been invested to propose XML schemas as ontology standards in the construction and manufacturing industry as well as for business applications. In the A/E/C domain, ifcXML and aecXML are the most popular XML schemas.

There exist tools that can automatically translate ifcXML from IFC/EXPRESS source (Liebich 2001). IfcXML enables the exchange of IFC data in XML formats. IFC (Industry Foundation Classes) is a data representation standard primarily for architectural and construction product data (ISO 1994). There have been efforts to extend IFC to include cost estimating and project management information (Thomas et al. 1999).

The ifcXML schema is a fairly extensive document with over 400 pages. IfcXML deals not only with geometry and product data, but also intends to support life cycle project information including architecture, HVAC, construction and facility management.

AecXML was initially proposed by Bentley Systems in 1998, and is now being part of the IAI (International Alliance of Interoperability). AecXML provides XML-based schemas to describe information specific for data exchange among participants involved in the design, construction, and operation of buildings, plants, infrastructure, and facilities (ISO 2002). The schemas currently under development include:

- COS (Common Object Schema)
- Infrastructure
- Structural
- FM (Facility Management)
- Procurement
- Project Management
- Plant
- Building Performance

There are many working groups within each domain to define XML schemas for specific applications. For example, the Project Management group is working on ApplicationForPayment schema, contract schema and other schemas. Table 1 summarizes the current state of the schemas posted on the URL site (http://www.aecxml.org).

<table>
<thead>
<tr>
<th>Working group</th>
<th>Schemas available in draft version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure</td>
<td>LandXML</td>
</tr>
<tr>
<td>Project Management</td>
<td>ApplicationForPayment, Contract</td>
</tr>
<tr>
<td>Plant</td>
<td>EquipmentDesignRequest</td>
</tr>
<tr>
<td>Building Performance</td>
<td>QbXML</td>
</tr>
</tbody>
</table>
In this work, we focus our research in the project scheduling and resource allocation area. While ifcXML schema exists, the “aecXML” schema\(^1\) employed in this study is the draft version developed by Primavera Systems in 1998. The schema is focused on project scheduling, and was based on the Primavera Project Planner (P3)\(^\text{TM}\) software.

**ONTOLOGY MAPPING BETWEEN PSL AND XML**

**MAPPING CONCEPTS BETWEEN PSL AND XML**

The first task is to map the terms related to project scheduling defined in PSL, ifcXML and aecXML.

In a typical construction project, a project schedule consists of a set of activities and the dependency relationships among the activities. Construction activities can generally be categorized into one of three types: production activities, procurement activities and administrative activities. Each activity has certain attributes associated with it, such as start date and duration.

Dependency relationships describe the constraints defining the order in which the activities must occur to complete the project (Gould 2002). There are four typical dependency relations: Finish to Start, Finish to Finish, Start to Start, Start to Finish. Figure 1 depicts the dependency relationships and their respective definitions. For example, the “Finish to Start” relationship between activity A and activity B means that B does not begin until A completes, and the “Finish to Finish” relationship means that A need to complete before B does.

![Dependency relationships among activities](image)

Figure 1: Dependency relationships among activities

In PSL, there are four basic classes: object, activity, activity occurrence and timepoint. Each activity in a project schedule can be roughly mapped into an activity occurrence in PSL, while time point is used to specify the beginning point and the end point of an activity occurrence. In PSL extensions, PSL provides some terms to describe the dependency relationship among activities. For example, the terms *before-start* and *before-start-delay* in PSL correspond to the “Start to Start” relationship in a project schedule. The PSL sentence *(before-start occ1 occ2 occ3)* specifies that the beginning time point of *occ1* is earlier than the beginning time point of *occ2*, while *(before-start-delay occ1 occ2 occ d)* means that *occ2* begins at least *d* time points after *occ1* begins.

---

\(^1\) The schema employed here is a version recommended by Professor Thomas Froese of University of British Columbia during his sabbatical at Stanford University.
For ifcXML, each activity in a project schedule can be roughly mapped to a Task element. The scheduling information about an activity is expressed in the WorkSchedule and ScheduleTimeControl elements. The WorkSchedule element holds the overall scheduling information, such as the start time and duration, while the ScheduleTimeControl element holds further descriptions of scheduling information, such as actualStart, earlyStart, lateStart and scheduleStart. The RelSequence element is used to express the dependency relationships among activities.

The aecXML schema follows closely the Primavera P3™ tool. Primavera Project Planner (P3)™ provides advanced project scheduling functions. The mapping from a project schedule in P3™ to aecXML schema is relatively straightforward. In the aecXML schema, there are activity, dependency and timepoint elements corresponding to the concepts in a project schedule.

EXPRESSING PSL IN XML-BASED SCHEMAS

IfcXML and aecXML are based on a meta-markup language (XML), while PSL is based on a formal logical language (KIF). XML has only limited representation capability to represent constraints and rules. Since PSL is built on first order logic, it is more expressive than XML-based schemas. Not all PSL sentences can be directly translated into XML, and some of the PSL logical statements are difficult to translate into ifcXML and aecXML.

Most PSL sentences that deal with basic facts can be expressed in XML format, for examples:

- \((\text{Beginof occ1 t1})\)
  This PSL sentence can be translated into ifcXML by creating a task occ1 and an associated WorkSchedule element, where the value of startTime attribute is t1.

- \((\text{before-start occ1 occ2 occ3})\)
  For this sentence, we can create two tasks occ1 and occ2, and define occ3 as the task of the whole project. We can then use RelSequence element to express the relationship between occ1 and occ2.

In general, the PSL sentences dealing with logic rules will be difficult to translate into XML directly. Some example situations are listed below:

- PSL sentences with existential or universal logic token (forall and exists), for examples:
  \((\text{forall } (\nu_1 \ldots \nu_n) (\Rightarrow \psi \theta))\)
  \((\text{exists } (\nu_1 \ldots \nu_n) (\text{and } \psi_1 \ldots \psi_m \theta))\)

- PSL sentences with deduction or logically equivalent tokens (\(\Rightarrow\) and \(\iff\)), for examples:
  \((\Rightarrow \text{occ1 occ2})\)
  \((\iff \text{occ1 occ2})\)

- Some PSL sentences with logic relations, for example:
  \((\text{during occ1 occ2 occ3})\)
  The PSL sentence \((\text{during occ1 occ2 occ3})\) means that the beginning and ending time points of occ1 are between the beginning and ending time points of occ2, and both...
occ1 and occ2 are subactivity occurrences of occ3. In ifcXML and aecXML, however, we do not have corresponding elements to express this logic relation. Consequently, it is difficult to translate this PSL sentence into ifcXML or aecXML.

One solution to this problem is to embed the whole PSL logic sentence as an XML attribute. For example, we can express the example PSL logic sentences in an XML structure as:

```
<LogicRules>
  <PSLsentence ID="01" rule="(forall (v_1 ... v_n) (\rightarrow \psi \theta))">
  <PSLsentence ID="02" rule="(exists (v_1 ... v_n) (\land \psi_1 ... \psi_m \theta))">
</LogicRules>
```

Embedding PSL sentences in an XML structure does not provide the meaning of the rules, since most XML parsers do not support rule processing. Nevertheless, the sentence can be exchanged verbatim between applications, if necessary.

On the other hand, we can always translate the scheduling information in ifcXML or aecXML files into PSL, as long as the PSL ontology covers all the concepts in the ifcXML and aecXML schemas.

**TRANSLATION BETWEEN PSL AND XML**

**BUILDING A PSL PARSER**

Presently, no generic PSL parser exists. Our first task was to build a PSL parser for the project scheduling information in Java. The basic process of a PSL parser works as follows: When the PSL parser reads a PSL logic sentence, it calls a corresponding function, which in turn parses the information in the sentence according to the PSL syntax. The information will be stored as objects and vectors, so that other functions and applications can retrieve and use the information. Figures 2 shows the example code segment from the PSL parser.

```java
private void parseDependency(String line, String type){
    String id, id1, id2; float ww;
    StringTokenizer st = new StringTokenizer(line, " 	
\r\f()");
    st.nextToken();
    id1 = st.nextToken(); id2 = st.nextToken();
    id = "depend" + depid;
    dependency dep = new dependency(id, id1, id2);
    dep.setType(type);
    dependencies.addElement(dep);
    depid = depid + 1;
}
```

Figure 2: Sample code of the PSL parser

One simplification we made in the PSL parser is that all PSL sentences are expressed as relations rather than functions. PSL syntax is based on KIF. In KIF, each function can be expressed as a relation. For example, the following two PSL sentences are equivalent:

- \((\text{begin-of} A \ 17)\)
- \((= (\text{begin-of} A) \ 17)\)

The difference is that in the first sentence the term \(\text{begin-of}\) is used as a relation, while in the second sentence the term \(\text{begin-of}\) is used as a function. In KIF, each function has a unique
value; for example, in the second sentence, the value of the function \((\text{begin-of } A)\) is 17. In contrast, the value of a relation is either true or false; furthermore, relations can have disagreement on the last element. For examples, the relations \((\text{before } t1 t2)\) and \((\text{before } t1 t3)\) differ. As a result, every function is a relation, while not every relation can be expressed as a function. Therefore, using relations is usually more convenient than using functions and minimizes unnecessary confusions and complexities in implementing the PSL parser.

The PSL parser developed so far can only parse predefined PSL terms. We are currently investigating the possibility to build a generic PSL parser in Java using a parser generator. A parser generator is a tool that reads a grammar specification and converts it to a Java program that can recognize matches to the grammar. Java Compiler Compiler (JavaCC) is one of such popular parser generators for use with Java applications (SUN 2002). We are currently building a generic PSL parser using JavaCC.

**BUILDING XML PARSERS**

To build parsers for ifcXML and aecXML files, we use Apache Xerces Java Parser (Apache 2002). Xerces Java Parser provides XML parsing and generation, and implements the W3C XML and DOM (Document Object Model) standards, as well as the SAX (Simple API for XML) standard. The parsers are highly modular and configurable.

The basic processes of the ifcXML and aecXML parsers are essentially the same. Both parsers use Xerces API to parse the information from XML files, and store the information as a linked list. Other functions and applications can iterate over the list to retrieve the information. The difference between the ifcXML parser and the aecXML parser lies in that ifcXML file and aecXML file use different tags and tree structures to represent a project schedule. Figures 3 and 4 show the sample code segments from the ifcXML parser and the aecXML parser respectively.

```java
public LinkedList getRelSequenceGroup(){
    LinkedList RelList = new LinkedList();
    NodeList nodes = document.getElementsByTagName("RelSequence");
    for(int i=0;i<len;i++){
        Element e=(Element)nodes.item(i);
        String[] attr = new String[5];
        attr[0] = (String)e.getAttribute("id");
        ... RelList.add(attr); } 
    return RelList; }
}
```

**Figure 3: Sample code of the ifcXML parser**

```java
public LinkedList getDependencies(){
    LinkedList DependencyList = new LinkedList();
    NodeList nodes = document.getElementsByTagName("dependency");
    int len = (nodes != null) ? nodes.getLength() : 0;
    for(int i=0;i<len;i++){
        Element e=(Element)nodes.item(i);
        String[] attr = new String[7];
        attr[0] = (String)e.getAttribute("dependencyid");
        ... DependencyList.add(attr); }
    return DependencyList; }
```

**Figure 3: Sample code of the ifcXML parser**
Figure 4: Sample code of the aecXML parser

**TRANSLATION PROCESS**

As shown in Figure 5, the translation process between PSL and XML is straightforward. To translate PSL files into XML files, first we use a PSL parser to parse the PSL logic sentences. We then map the terms in PSL into XML tags. Finally we construct the XML trees according to the ifcXML schema and aecXML schema, and output the file in the corresponding formats.

The reverse process is similar. To translate ifcXML and aecXML files into PSL files, we use the ifcXML and aecXML parsers to parse the information from the XML files. We then map the XML tags into PSL terms, and output the PSL logic sentences according to PSL syntax.

**EXAMPLES**

**EXAMPLE 1: SAMPLE PROJECT FROM VITE**

We select a sample project from Vite™ to test our translators among PSL, ifcXML and aecXML. Vite™ is a project and organization modeling system designed to assist in developing organizational structures and identifying potential problems with project cost, time, or quality. As shown in Figure 6, the sample project is to design and fabricate a chip set for a new personal digital assistant (PDA) product. There are 12 activities in this project. Among the 12 activities there are three milestone activities: ‘Start Project,’ ‘Ship Tapes to Foundry’ and ‘Fab, Test and Deliver.’ The activity ‘Design_Coordination’ is to maintain the overall control of the project.
The scheduling information in the example project can be expressed in a PSL file. Figure 7 shows part of the PSL file, which includes a set of logic statements to describe activities and dependency relationships in the project schedule.

```
(and
  (project TUTO)
  (doc TUTO "TUTORIAL Project")
  (beginof TUTO 9/18/1998)
  (subactivity-occurrence ID100 TUTO)
  ...
)
(and
  (activity-occurrence ID100)
  (doc ID100 "Assemble and verify_RTL")
  (beginof ID100 12/17/1998)
  (duration-of ID100 18)
  (after-start ID100 ID170 TUTO)
  (after-start-delay ID100 ID170 TUTO 0)
)
```

Figure 7: Sample PSL file

Figure 8 shows part of the ifcXML file translated from the PSL file. As discussed earlier, a Task element in ifcXML maps to an activity in a project schedule. Thus the ‘taskid’ attribute in ifcXML maps to the identifier of an activity occurrence in PSL. As a result, the WorkSchedule element is associated with the corresponding activity by using the same identifier as its identifier attribute. Similarly, the RelSequence element, which depicts the dependency relationships among activities, is associated with the predecessor and successor activities through its ‘relatedProcess’ and ‘relatingProcess’ attributes.

```
<WorkScheduleGroup>
  <WorkSchedule identifier="ID100" duration="18.0" freeFloat="0.0" totalFloat="0.0" startTime="12/17/1998" finishTime="1/4/99"/>
</WorkScheduleGroup>
<TasksGroup>
  <Task taskid="ID100" description="Assemble and verify_RTL"/>
  <Task taskid="ID700" description="FullChipSynth"/>
</TasksGroup>
<RelSequenceGroup>
  <RelSequence id="depend0" relatingProcess="ID100"
    relatedProcess="ID170" timeLag="0.0" sequenceType="after-start"/>
</RelSequenceGroup>
```

Figure 8: Sample ifcXML file

Figure 9 shows part of the aecXML file translated from the PSL file. AecXML schema has most elements corresponding exactly to the concepts in a project schedule. Once we have mapped the PSL ontology to the concepts in a project schedule, translation between PSL and aecXML requires little extra efforts.
As shown in Figures 7, 8, and 9, all information in the PSL file is successfully translated into ifcXML file and aecXML file, and vice versa.

**EXAMPLE 2: MORTENSON CEILING PROJECT**

To test the scalability of the prototype translators, the Mortenson Ceiling Project is employed to illustrate the ontology mapping process. The Mortenson Ceiling Project is a portion of the construction of the Walt Disney Concert Hall, built by Mortenson Construction, and designed by Frank O. Gehry & Associates. Figure 10 shows the schedule in Primavera Project Planner™. In this project, there are 191 activities and 459 dependency relationships.

Using the PSL wrapper, we extract the scheduling information from Primavera Project Planner™, and convert it into a PSL file, as illustrated in Figure 11. There are more than 2000 logic sentences in the generated PSL file. Using the PSL to XML translators, we successfully translate the PSL file into ifcXML and aecXML files. Figures 12 and 13 show the corresponding ifcXML and aecXML files, respectively. This example demonstrates the robustness of the prototypes developed for information exchange between PSL and XML-based standards.
(and
  (activity-occurrence 1620-91101)
  (doc 1620-91101 "Hang Drywall@Studs (Dt17050) - M1/3 Lvl 6 Elem1")
  (beginof 1620-91101 2/11/2002)
  (duration-of 1620-91101 10)
  (freefloat 1620-91101 0)
  (totalfloat 1620-91101 42)
  (after-end 1620-91101 1620-97101 CEIL)
  (after-end-delay 1620-91101 1620-97101 CEIL 1)
  (after-start 1620-91101 1630-91101 CEIL)
  (after-start-delay 1620-91101 1630-91101 CEIL 0)
)

Figure 11: Sample PSL File

<WorkSchedule identifier="1620-91101" freeFloat="0.0" totalFloat="42.0"
startTime="2/11/2002" finishTime="2/21/2022"/>
<Task taskid="1620-91101" description="Hang Drywall@Studs (Dt17050) - M1/3 Lvl 6 Elem1" >
<RelSequence id="depend79" relatingProcess="1610-91101"
relatedProcess="1610-97101" timeLag="1.0" sequenceType="after-start"/>
<RelSequence id="depend80" relatingProcess="1610-91101"
relatedProcess="1620-91101" timeLag="0.0" sequenceType="after-start"/>

Figure 12: Sample ifcXML file

<activity activityid="1620-91101" description="Hang Drywall@Studs (Dt17050) - M1/3 Lvl 6 Elem1" dependencyids="depend159,depend160"/>
<dependency dependencyid="depend159" predecessor_activity_id="1620-91101"
successor_activity_id="1620-97101" relationship="after-start" lag="1.0"/>
<dependency dependencyid="depend160" predecessor_activity_id="1620-91101"
successor_activity_id="1630-91101" relationship="after-start" lag="0.0"/>
<timepoint timepointid="tp102" activityid="1620-91101" description="begin Hang Drywall@Studs (Dt17050) - M1/3 Lvl 6 Elem1" atTime="2/11/2002"/>
<timepoint timepointid="tp103" activityid="1620-91101" description="end Hang Drywall@Studs (Dt17050) - M1/3 Lvl 6 Elem1" atTime="2/21/2022"/>
<occurrence activityid="1620-91101" begin="tp102" end="tp103"
duration="10.0" freefloat="0.0" totalfloat="42.0"/>

Figure 13: Sample aecXML file

CONCLUSIONS

Different ontologies exist for different application domains. IfcXML, aecXML and PSL are candidate ontology standards that could be employed by the construction industry. To achieve interoperability among different construction applications, we have developed translators for information exchange among PSL, ifcXML and aecXML and tested for a typical project schedule. We identify the PSL sentences, which could be difficult to translate into XML format. Our current research includes translating complex PSL logic sentences into ifcXML and aecXML structures. In addition, we are investigating the potential use of logic-based PSL for conflict resolution and consistency checking of a project schedule.
ACKNOWLEDGEMENTS

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REFERENCES


DYNAMIC MODELLING METHOD FOR SITE FACILITIES TO SUPPORT COST SIMULATION

Steffen Scheler¹ and Raimar J. Scherer²

ABSTRACT
This paper suggests a solution for an area of growing importance to construction IT - the planning and managing of construction site installations. On the basis of a consistent product model of site facilities enabling variable settings over time, a cost estimation of the site facilities with respect to possible changes in the site model structure is performed. A dynamic modeling approach is used to represent temporal changes in the structure of the partial site models. Knowledge base instantiation for each specific (time-dependent) site facilities configuration is achieved with the help of methods using the description logic paradigm. Geometry data about the building and the site are imported in the site evaluation tool via an IFC interface. The instantiation of site facilities elements in the knowledge base is accomplished by means of a dynamic classification method. In this way, the needed modifications of the model structure at specific points in time are supported.

The dynamic model enables exchange of partial models and hence supports the development of comparisons between alternative site facilities instantiations which in turn can greatly aid the concurrent decision processes during site planning and during construction, e.g. by parallel re-scheduling of activities by the project leader or by design changes made by the contractor for better constructability.

KEYWORDS
site planning, site facilities modeling, cost analysis, simulation, dynamic classification

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INTRODUCTION

The distribution and flow of resources on the construction site strongly influence the construction management process and the overall success of each project. Therefore, it is of utmost importance to plan smooth and faultless work and material flows for the construction process at the site already at the outset, i.e. in the design phase. As a whole, the main tasks of site facilities planning are:

- definition of the type of facilities,
- spatial arrangement of the chosen elements in accordance with time and cost factors, such as the requirement for minimal transportation overheads on the site, e.g., by crane operations scheduling.

In general, “building production processes” cannot be exactly planned in advance as they are subject to unforeseeable changes during project execution. These processes are defined as dynamic site processes. They can be further subdivided into three categories, as shown in Table 1.

Table 1: Three types of dynamic site processes

<table>
<thead>
<tr>
<th>dynamic site processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>continuously changing site</td>
</tr>
<tr>
<td>phase-dependent</td>
</tr>
<tr>
<td>unexpected</td>
</tr>
<tr>
<td>straight-line construction</td>
</tr>
<tr>
<td>changes after construction</td>
</tr>
<tr>
<td>technological change</td>
</tr>
<tr>
<td>due to interferences</td>
</tr>
</tbody>
</table>

Furthermore, the diversity of site facilities in terms of types and temporal aspects require substantial planning efforts, emphasized by the continuous change of location and the very different requirements of each particular site. Therefore, the early recognition of dynamic site processes and their consequences is also a critical cost factor. This is especially important in view of the concurrent engineering methodology where space and time factors on the site are required to be concurrently and holistically considered for all involved work sections, at the same time weighing up different alternatives with regard to risks, quality, time and costs.

Dynamic layout planning with respect to space management for the purpose of minimizing transportation and relocation (Zouein and Tommelein 1999), as well as the consideration of geometrical and topological aspects (Medjdoub and Yannou 2001) are extensively studied. Work space planning for project specific activity space requirements has also been investigated in recent research, e.g. in (Akinci et al. 2000) where 4-D modeling is used for the tackling of scaffolding problems. However, in order to achieve more efficient decision support, beside mathematical geometry / time considerations regulatory rules and engineering knowledge of the domain should also be taken into account.

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1 Here only the transportation processes directly on the site are meant. For example, an inadequately positioned stockyard can lead to an immense increase of crane transportation time and costs, and consequently, through the summed up idle times of all crane-dependent processes, increase or even maximize the overall costs.
Combining geometric and time requirements with regulatory and heuristic rules and construction details available in building product models (e.g. for accident prevention) is the primary objective of the research presented in this paper. The developed approach is strongly focused on the adequate representation of building product model data for the purpose of the building production process and its appropriate utilization in dedicated decision support tools for variant site facilities planning, including cost estimation. Special emphasis is put on the adaptability to the dynamically changing situations on the construction site, acknowledging that “… the pitfalls between adaptive and adaptable systems … and between contextualized information representation and serendipity will hopefully lead us to new ideas” (Fischer, 2001).

SITE FACILITIES MODEL

MODEL STRUCTURE

A simple site installation requires site facilities\(^1\) on a correspondingly low level (e.g., some container). Consequently, the product model representing the site installations is also relatively simple. However, when additional, more complex site facilities are added (crane and therefore haul roads, container, etc.), the site will no longer contain only simple installations. Respectively, another more complex product model will be required as well. To enable dynamic changes to the model as such, new and more flexible solutions that are not provided by traditional object-oriented modeling approaches are needed.

Different partial models of the site product model are necessary to manage site facilities aspects efficiently. Such models are for example domain models of geometry aspects, the site facilities elements, personnel administration, cost management in view of site facilities etc.

To enable adequate extraction and utilization of the knowledge contained in these models, they need first to be appropriately and consistently combined. There are different approaches known for that purpose (Katranuschkov 2001).

Model harmonization aims at providing a general methodology which should enable the development of a priori consistent data models, i.e. before their use in any practical situation. It is an approach of “integration by intention”. Typical efforts in that respect are undertaken in STEP (ISO 10303) and in IAI/IFC (IAI 2001).

In contrast model integration aims at establishing a posteriori, i.e. by already existing data models, a semantically conflict-free environment with guaranteed overall consistency. It is an approach of “integration by definition”. An outstanding area of such efforts is the development of federated systems for existing enterprise databases.

Finally, model mapping also aims at the development of methods that can be used to bring together non harmonized model data. However, instead of attempting to integrate the involved models when the environment is designed, the model mapping methods target the transformation of the data contained in one model into the representation required by another model at run-time. Thus, here an “integration by demand” is hoped to be achieved.

\(^1\) In this paper, it is important to strictly differentiate the two commonly known terms “site installations” and “site facilities” that are often used synonymously in other work. Here “site installations” means the whole construction site including building, pit, all placements etc., whereas “site facilities” are the elements for the production process on the site only, i.e. the wandering manufactory.
However, all these approaches are not very suitable for the dynamically changing model of the site facilities. In contrast to building structures, site facilities are less studied and more difficult to classify in advance. Therefore, the achievement of a harmonized model is arguable. Model integration as used in database research presets existing partial models of more or less fixed structure which is not the case for the building production process. Model mapping provides at a first glance a viable approach, but available experience shows that it only succeeds when the source/target models of the mapping are to some degree similar in structure.

In our case models are not very large but quite differently structured. Moreover, ad hoc decisions can often lead to changes in the model structure that are difficult to predict and specify in advance. Therefore we suggest the use of an ontological framework based on available IFC specifications but utilizing a different, more flexible modeling paradigm built upon the description logic approach. In this way, the needed dynamic modifications of partial models during the construction process, requiring different partially organized product models, can be efficiently and dynamically performed.

The ontology describes the structure of the model and may identify constraints on the relationships between its elements. It is comprised of (1) concepts, (2) relationship identifiers, (3) a concept hierarchy /taxonomy/, (4) a directed transitive relationship function that relates concepts non-taxonomically, and (5) a set of axioms expressed in logical language.

In fact, it is an explicit specification of the conceptualization used by the knowledge base which is especially important for the sharing and reuse of knowledge (Divita et al. 2001). Furthermore, it strictly distinguishes between count terms, representing tangible objects such as known site elements, and mass terms, representing intangible objects such as status descriptions. Another important aspect of the ontology is the provision of variable object / attribute settings over time (identity on historical basis).

**MODEL COMPONENTS**

The site facilities model is comprised of partial models for (1) site installed buildings, including all stationary and mobile building objects for the site manufactory, (2) site facilities depots, such as work and storage places, (3) haul roads, (4) plants, including all stationary and mobile vehicles on the site, and (5) media facilities, such as power or water supply.

The kernel part of the site model defines the placement and the global position of the site installation as well as the basic types of site elements as shown on Figure 1 below.

Most of the partial models require adequate consideration of dynamic model changes which may happen simultaneously in more than one partial model. For example, haul roads are considered in relationship with cost and time factors with the help of a dedicated site design tool. In order to reflect properly the dynamic changes of the haul roads both in terms of space (relocation) and time (adding, removing, replacing of equipment, machines, work crews), a partial modification of the structure of the initial model needs to be performed, and not only simple changes of parameter values.
With respect to the ontological taxonomy the necessary rules for default class definition are separated into (1) a public interface including predefined references to the model structure, (2) a protected interface defining confidential data links such as cost structuring and (3) a user interface reserved for the implementation of additional user-defined properties. An example of a default element, implementing such rules is shown below.

Figure 1: Site model kernel
The hierarchical class structure and the network of implemented and linked rules provide the backbone of the model. These rules represent engineering knowledge, normative or regulatory constraints and heuristic site management rules based on past experience.

Table 2 below presents an example of such inter-linked rules for different types of site containers for accommodation and office usage.

Table 2: Selected rules with occupancy and measurement for site container.

<table>
<thead>
<tr>
<th>Measurement (L * W in meter)</th>
<th>Site container type</th>
<th>Max. persons</th>
<th>Rules for occupancy rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95 * 1.10 m</td>
<td>single toilet</td>
<td>10</td>
<td>persons on site required of</td>
</tr>
<tr>
<td>2.99 * 2.44</td>
<td>10” without toilet</td>
<td>4</td>
<td>site accommodation</td>
</tr>
<tr>
<td>6.06 * 2.44</td>
<td>20” without toilet</td>
<td>8</td>
<td>site accommodation</td>
</tr>
<tr>
<td>6.06 * 2.44</td>
<td>20” with toilet</td>
<td>5</td>
<td>site accommodation</td>
</tr>
<tr>
<td>6.06 * 2.44</td>
<td>20” without toilet</td>
<td>2</td>
<td>site office</td>
</tr>
</tbody>
</table>

In this table, rules provide respective dependencies between the separate concepts given in the table columns. Measurements for geometric space ordering (from ontological viewpoint ‘count’ terms) are linked with site container types, which are constrained in turn by occupancy rules, linking the concepts from columns 2 and 3. Finally, container usage (a ‘mass’ term) is linked with the occupancy rate provided in column 3. When chained, these simple rules can lead to ‘surprising’ solutions, difficult to anticipate in advance.
Site facilities elements (e.g., crane, container, storage yards) are represented as instances of the pre-defined class hierarchy. The instantiation of these elements, explained further below, is performed by using a dynamic classification method based on description logic. When a partial model is modified (e.g. site position inside pit, machine or social facilities), the instances of the whole model – respectively linked to the pre-defined elements - are analyzed and, if necessary, re-classified to reflect the changed structure.

However, in contrast to the typical object-oriented approach, the instantiation process is not a simple assignment of values to object attributes followed by association of these objects to respective classes. Instead, object classification is performed dynamically, governed by value ranges determined on the basis of cost estimation elements.

MODEL SUPPORTED COST SIMULATION

Today, a major measurement of good project management is cost reduction\(^1\). In our approach the cost factor is extracted from the instantiated knowledge base depending on the model structure filled with the objects corresponding to the chosen solution. This follows best practice management experience requiring continuous target performance comparison (cost-volume-profit analysis\(^2\)).

A separate cost model (siteFacility_cost) - strictly derived from the IFC model specification (IfcDocumentExtension.IfcCostScheduleGroup) - enables the tackling of costs independently of the other models in the framework. In the cost domain we differentiate between three basic types of costs:

- **Holding time costs** that are dependent on the hold-back process (for example, the hired site container “produces” lease costs both with and without usage). This type is different from the owning costs which encompass insurance etc. Holding costs are subdivided in amortization costs and hire charges. They provide the most important time-dependent cost type w.r.t the instantiation of the site facilities model.

- **Fixed costs** include one-time expenses for site installations assembling and disassembling. They are further subdivided into assembling costs, disassembling costs and extra costs (described by lump sums).

- **Additional costs** are integrated in the site facilities model in view of future model extensions. Currently they are simply related to the extra costs.

Each site facilities element owns the important attribute of shared costs. The knowledge based relation of shared costs is composed of the different cost types enabling the specification of the cost attributes of the site facilities elements.

Figure 2: Site facilities model configuration for comparison of cost variants

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\(^1\) Other typical measurements include time, capacity, quality and quantity.

\(^2\) The term “cost-volume-profit analysis” is used to denote the German practice of target and actual cost comparison where the tender costs and the work execution estimate are compared with the (e.g. monthly) performance report (Pilcher, 1992).
The essence of the developed method is in performing partial modification of the initial product model, and not only simple changes of parameter values. In this way, different alternatives can be compared more accurately which enables adequate scheduling of the site facilities costs depending on the design cost estimation and the actual construction progress and needs. Figure 2 outlines the principal procedure.

**REPRESENTATIONAL AND IMPLEMENTATION ASPECTS**

**ENVIRONMENT AND LANGUAGE FOR DYNAMIC MODELLING METHOD**

The LOOM system (Brill 1993) has been chosen as basic tool for the implementation of the developed approach. LOOM is a powerful tool in the domain of knowledge representation. It integrates object-oriented modeling with declarative knowledge-based processing and enables the implementation of dynamic classification. Other systems that include dynamic concept classifiers in the so called Second Generation of the Description Languages family, such as CLASSIC (Borgida et al. 1989), do not provide incremental updating of definitions (useful in large applications) and no production rules.

The heart of the LOOM environment is its inference engine (the Classifier). Its major task is to compute subsumption relationships between concepts (unary relations) as well as to identify instance-of relationships. The description classifier utilizes a forward chaining method, whereas the query system uses backward chaining (so called backward chaining query processor).

The expressive features of the LOOM environment are provided by the realization of two logical languages - “description logic” and “predicate calculus” (MacGregor 1999). The predicate calculus language is more expressive but the classifier works better with the description logic expressions.

A useful extension is the included context mechanism provided by the unique combination of object model structures and production rules. Another important aspect is that not all instances have to be classified by subsumption. The developer can choose between tight instantiation and automatic classification of the instances. Thus, LOOM queries are almost as efficient as hand-coded queries (MacGregor 1999).

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1 Recently, a successor of LOOM called PowerLoom has been introduced to the market as well. However, the basic LOOM system provides sufficient functionality for the goals of this research. Therefore it was not found necessary to be exchanged.
Establishing Knowledge Base and Implementation

The LOOM system is used within an Allegro LISP environment. The GUI is provided by a Web Browser with a XML interface. The domain knowledge base comprising the above mentioned partial models is instantiated with initial class definitions, rules, facts, defaults and alternatives, whereby for each partial model separate rule sets are defined, e.g. site-container-measurement-coordination versus site-container-person-fulfill-management (cf. Table 2 above). This semantic network is easily set up with the help of the description classifier. The attributes that characterize each class are pre-determined whereas all necessary conditions for a further dynamic specification of classes and relations automatically result from the already established logical connections.

In our approach concepts are the classes of a specific partial model, e.g. site-container, whereas the different elements allocated to the classes, e.g. container-type-xy, are instances in the knowledge base. A class defined in the model marks the sufficient conditions for the classification that are the criteria for class membership. Necessary conditions which represent declarative and procedural knowledge are applied to each member instance of the class. An object that satisfies all sufficient conditions is classified to be a member of the pre-defined class. Each object fulfilling the sufficient conditions can be attached to the class and inherits all necessary conditions from the attached class that enables active knowledge transfer. It is furthermore possible that objects are instances of different classes at the same time, and due to the dynamic change of the object properties, an evolution of the class membership is possible. Thus, re-instantiation at run-time, independently of the initially instantiated model structure is made possible.

As an example, consider the pre-defined macro “implies” (Brill 1993). It specifies that a strict implication holds between two relations or concepts. Given two rules, A (container-person-relation) and B (container-measurement-relation), and provided that “implies” holds for all their subparts and a new concept C is defined as (container-person-measurement-relation), when classifying C the classifier will inherit the description of A and B. After unifying and normalization (creating a new subpart definition) it will attach the normalized rule ‘C “implies” all subparts’ (formerly “inherit”) and will then eliminate the two originally inherited descriptions from A and B since they are now redundant. Thus, dynamically, a changed taxonomy will be created by the classifier as illustrated in Figure 3.

An important aspect for future extension is the implementation of shared database support. This can be achieved e.g. with the help of the PERK system (Karp et al. 1994) which enables the communication between LOOM and a RDBMS.

Figure 3: Inheritance and dynamically change of knowledge structure
SUMMARY
The main goal of the presented approach is to enable product model based support for a tool that can simulate different states of site installations, especially focusing on site facilities.

The basic elements of the site facilities and their inter-relationships are generically represented in a site facilities product model. The structure of this model is highly modularized to enable (1) the adequate exchange and modification of partial model data, and (2) the definition and implementation of interfaces to already existing building model data, as e.g. IFC.

As a whole, the site facilities modeling and cost simulation system is a distributed decision support system which cycles through the separate analysis subtasks (e.g., geometric site configuration, equipment level, cost estimation) in correspondence with the overall analysis goals set up according to the initially generated model structure. In this process, an essential role is attributed to the substitution of partial models to enable the simulation and evaluation of alternative solutions. The consistency of the overall model is thereby maintained through the respectively carried out re-classification of the involved product objects. The re-classification itself is enabled by a dynamic classification method implemented with a tool from the domain of knowledge representation technology. The innovative aspect of the approach is in the dynamic modification of whole model parts and not only the re-classification of instances in a single model. The enabled comparisons between alternative site facilities instantiations support the concurrent decision making process through all phases of site planning and construction, e.g. by parallel re-scheduling of activities by the project leader, by design changes made by the contractor for better constructability, by considering the mutual inter-dependencies of spatial, time and cost aspects etc. Hence, the presented system can be a valuable support tool for concurrent engineering work, especially for the fast evaluation of the consequences of alternative decisions with respect to quality and costs.

The system is designed for building sites up to 2–6 Mio. US$ only. For testing and validation, a real project in an inner city area (successful finished without this system), with two site process changes during the construction phase has been used.

REFERENCES


ABSTRACT
A recent UK government report identifies that too many buildings perform poorly in terms of flexibility of use, operating and maintenance costs, and sustainability. The industry needs new and innovative ways to overcome the poor performance of its products through better design. Design is a knowledge-intensive process that has impacts on the whole lifecycle of a project. Collaboration between the different stages of a project lifecycle is required to transfer knowledge to those involved in design. This paper presents an ongoing research that investigates the role of Knowledge Management (KM) in supporting Concurrent Engineering (CE) for improving structural design processes. It discusses, based on a case study of a UK construction consultant, the types of knowledge involved, the problems associated with it, and the potential of KM in overcoming these problems. The paper concludes that KM supports concurrent design through the creation of knowledge-sharing environments.

KEY WORDS
Knowledge management, structural design processes, concurrent engineering, construction
INTRODUCTION

The UK government report by Egan (1998) states that “too many buildings perform poorly in terms of flexibility of use, operating and maintenance costs and sustainability”. This poor performance is due to several factors that influence the construction industry not only in UK but also in many parts of the world. One of the reasons for the poor performance is the “the separation of design from the rest of the project process” (Egan 1998). The industry, therefore, needs new and innovative ways to allow for more collaboration between the design stage and the other stages of a project lifecycle.

Structural design is a complex process that requires extensive knowledge. In fact, it is the knowledge and experience that make one design better than others. The design of large structures can take years often leading to changes in the design team i.e. the people completing the structural design may be different from those who started it (Garrett and Smith 1996). Furthermore, structural design requires that the complexity of each structural problem be considered alone, based on knowledge of best practices (codified knowledge) and experience (tacit knowledge). For example, the selection of a structural form or shape to provide a desired structural behavior is affected by many uncertainties e.g., loads, material strengths, soil conditions (Garrett and Smith 1996). Structural designers need to use existing knowledge and obtain new knowledge generated during the construction of projects. Deciding on the best way for facilitating the way this knowledge is used, obtained, and shared remains open to several research proposals.

Knowledge Management (KM) is a process that aims to manage organizational knowledge in order to improve performance. This puts KM at the forefront for creating more collaborative environments. In fact, KM may be a step forward in achieving efficient collaboration between the design process and the other processes of a project lifecycle. KM can therefore help structural designers to easily locate, access, and use the knowledge that they require so that optimization can be achieved in terms of constructibility, quality, cost, and maintenance.

This paper explores the role of KM in supporting CE to create knowledge-sharing environments for structural design. It starts with an overview of the design process and the existing approaches to improving structural design. A case study is used to identify the nature and type of knowledge involved, associated problems, and how they could be overcome.

STRUCTURAL DESIGN

“Design is one of the most intelligent tasks that humans perform” (Kumar and Topping 1991) and it is involved in almost every thing in our lives. The design process consists of activities and their information requirements. These activities are described by Chandrasekaran (1989):

“The design problem is specified by a set of functions to be delivered by an artefact, a set of constraints to be satisfied by the artefact during its functioning, and a repertoire of components assumed to be available and a vocabulary of relations between components. The solution to the design problem consists of a complete specification of the set of components and their relations, which together describe the instance of the artefact, which satisfies the requirements of its functions and constraints.”
The design of construction projects involves several inter-related sub-processes such as architectural, structural, and electrical design. Structural design is a complex process that is carried out to produce safe and stable structures. It is a sub-process of the design stage of any construction project and is carried out based on the requirements of and constraints on the proposed project. These requirements and constraints are surrounded by many uncertainties e.g., change of client requirements, environmental factors, assumed live and wind loads, partially investigated soil area, unpredictable earthquakes, etc. The process consists of many interrelated activities (Bell and Plank 1985; Kumar and Topping 1991; Evbuomwan and Anumba 1996; Austin et al. 2002). It consists mainly of: the identification of the nature and scope of the design task, the formulation of the mathematical statement of the design problem, and the evaluation of the design results to determine the adequacy of the developed solution (Grierson and Cameron 1988). Due to the constraints surrounding it, structural design usually consists of more than one design cycle to achieve an accepted final design (Grierson and Cameron 1988). Furthermore, activities that take place within the structural design process are influenced by several factors that are linked to human intelligence such as experience and engineering judgment (Bell and Plank 1985).

Structural design can be generally divided into concept and scheme design stage, and detailed design stage (Austin et al. 2002) although these have taken slightly different names sometimes. Decisions made during the concept and scheme design stage affect later stages. In fact, there is a considerable dependence, during this stage, on the experience of designers to ‘know’ how to design (Austin et al. 2002). Concept and scheme design stage is primarily concerned with information/knowledge gathering and decision-making to enable the team to propose a solution to the stakeholders needs. The transition from scheme design into detailed design brings with it a shift from negotiation and agreement being the principle driver for the design process to the coordination of the design activity becoming of greater significance to project success. Detailed design involves the detailed analysis of the chosen structure from the preliminary design and the sizing or proportioning of its components to satisfy different constraints (Kumar and Topping 1988).

EXISTING APPROACHES TO STRUCTURAL DESIGN IMPROVEMENT

Literature shows that there are several approaches to improving the structural design process and that many of them make potential inputs to enhancing the way the process is carried out. These approaches can be generally categorized into the following:

ALGORITHMS FOR ANALYSIS, MODELING, AND DESIGN OF STRUCTURES

Several software tools support the analysis, modeling, and design of structures. Some of these tools only support one or two of these stages while others support all the three stages. Examples of such tools are S-Frame, CADRE, STAAD, etc. In these tools, the system bases its calculations on the input received from the user and his/her selection from available features. This also involves several assumptions based on the user’s knowledge, experience, and engineering judgment.
EXPERT SYSTEMS

Knowledge-based expert systems are Artificial Intelligence (AI) tools that identified the importance of experts’ knowledge. While design databases represent solutions without capturing the knowledge behind them (the what, but not the why), knowledge-based expert systems attempted to codify the abstract reasoning processes of the expert into “if-then” rules. There are two types of expert systems namely, rule-based systems which contain design-independent knowledge, and case-based systems which contain design-dependent knowledge. Rule-based systems capture knowledge abstract reasoning rules independent of specific designs while case-based systems represent a memory of good and bad designs and design strategies together with the rationales that support them. Examples of structural design expert systems are described in Wang and Howard (1988) and Maher and Gomez (1996).

INTEGRATED DESIGN SYSTEMS AND ENVIRONMENTS

The complex design of structures consisting of many interacting subsystems requires many different disciplines, which needed to be integrated. This necessitated the development of computer based collaborative design environments. Projects carried out in this area can be put in two categories: the development of environments for allowing the different participants in the conceptual structural design process to interact using a shared graphical description of the design (Fruchter 1996) and the integration of engineering software design from conceptual design through detailed design and design documentation (Evbuomwan and Anumba 1996).

SYSTEMS FOR MODELING THE PROCESS

Modeling the design process has been researched by several authors e.g., Mostow (1985) and Austin et al. (2002). The later introduced three frameworks to model the stages of a design process: conceptual design; scheme design; and late design. The first framework is a generic process model that clusters the design activities in relation to the manner in which they were commonly addressed. The second assists in improving coordination as the project process advances. It represents a network of tasks connected by the flow of information between them. The third is an Analytical Design Planning Technique (ADePT), which helps in improving the planning of projects.

KNOWLEDGE MANAGEMENT APPROACH

The structural design process involves many knowledge-dependent tasks where knowledge exists in two forms (Nonaka and Takeuchi 1995): ‘tacit’ knowledge, which is stored in the brains of people, e.g., experience of engineers and their skills in performing certain tasks, and ‘explicit’ knowledge, which is codified in documents, drawings, databases, and expert systems, e.g., design regulations, design codes, etc. This section identifies the knowledge involved in structural design and the problems that are associated with it. It then introduces knowledge management as an innovative approach for facilitating knowledge sharing between the different stages of a project lifecycle to facilitate concurrent designs.
**KNOWLEDGE INVOLVED IN STRUCTURAL DESIGN**

Structural design is an iterative process that normally consists of more than one cycle. The number of cycles depends on several factors such as the availability of knowledge and expertise, and the nature of uncertainties involved in the project. Garrett and Smith (1996) describe the knowledge-intensive activities involved in structural design:

- Designers determine the structure’s functional requirements e.g. how many people will use the structure and for what purpose. These requirements depend on the proposed use of the structure and include both tacit knowledge such as experience in similar projects and explicit knowledge such as codes of design.

- Designers inspect the environment – soil conditions, seismic activities, and the wind loadings—where the structure will be built. For example, soil test only covers few points of a building area where interpretation of the results can be driven by several factors such as the availability of previous test results in the neighboring area (explicit knowledge) or previous involvement in a project within the same area (tacit knowledge). Sometimes social and political factors are also important.

- Designers usually generate various alternatives for the structure such as alternative structural configurations, component sizes, and material selections. They also predict behaviors such as stresses, deflections, and vibrations, as well as costs under great uncertainty. This involves a large amount of tacit knowledge such as why to consider specific solutions and how to anticipate the behavior of every one of the solutions.

- Construction companies use their tacit knowledge (e.g. expertise) to predict how they will build the structure, what resources they will use, how much it will cost, and how long it will take to build.

**KNOWLEDGE PROBLEMS**

The complexity of structural design depends on the type of the structure, purpose of its use, internal and external constraints, etc. Furthermore, the way a structure is designed depends on the availability of construction materials and equipment, and accessibility to data, information, and knowledge. Structural design problems that are connected to knowledge involve but are not limited to the following:

- Design is based, in many situations, on assumptions (Kumar and Topping 1991) and engineering judgment (Tyson 1991). These are usually based on knowledge and experience. However, even experienced engineers face difficulties when the required knowledge is not available and this can result in assumptions or judgments that may be invalidated when knowledge becomes more available (Kumar and Topping 1991).

- Feedback from the other stages usually results in redesign (Kumar and Topping 1991). Feedback to designers is necessary during the different stages of a project lifecycle. This, in many cases, forces designers to return to an earlier design and redesign it. If feedback is given during the construction stage, it would not allow
enough flexibility in redesign due to technical and/or contractual issues (e.g., variation orders).

- Knowledge obtained during the construction and maintenance stages is not properly shared with designers. A structural failure may occur because of inappropriate design. Knowledge about this failure (why it occurred, how it could have been avoided, etc) needs to be shared with the other designers within the organization so that the same mistake is not repeated.

- Improper management of design knowledge causes its loss (Bliznakov 1996; Hegazy et al. 2001). Design consulting firms are knowledge-intensive organizations where improvement in design depends on the availability of knowledge. Not having this knowledge easily accessible does not only result in less innovative designs but also leads to deterioration and gradual loss of the knowledge.

**CONCURRENT DESIGN THROUGH KNOWLEDGE MANAGEMENT**

Concurrent Engineering (CE) is an approach that supports: bringing together all members of a project to work in parallel; and making the different sources of information and knowledge available to designers at the early stages of design (Kannapan and Marshek, 1992). It aims at improving design and reducing the number of redesigns (Evbuomwan and Anumba, 1996).

Most knowledge problems –as seen above- are due to knowledge being unavailable when required or being held by people who do not or cannot share it with those who require it. In order to develop reliable plans for overcoming the knowledge problems identified above, strategies that support ‘knowledge-sharing’ should be implemented.

Knowledge Management (KM) is relatively new to construction organizations (Carrillo et al. 2000) and although there is no universally agreed definition, it is generally accepted that KM revolves around making knowledge available to users whenever they require it and this addresses one of the key issues in CE that is about supporting the knowledge sharing process. “Knowledge management enables the creation, communication, and application of knowledge of all kinds to achieve business goals” (Tiwana 2000). In fact, it is any process or practice of creating, acquiring, capturing, sharing and using knowledge, wherever it resides, to enhance learning and performance in organizations (Scarborough et al. 1999). A more construction-oriented definition is introduced by Al-Ghassani et al. (2001):

“KM can be defined as the process of capturing/gathering, storing and retrieving, transferring and sharing, modifying/updating, and using the different types of project knowledge that are mainly gained during a project’s lifecycle. The principal aim of KM, from a construction perspective, is to make this knowledge easily accessible, modifiable, and usable so that time is saved, performance is improved, and innovation is enabled in future projects. This knowledge covers all types of construction project and may be tacit or explicit, or in the form of best practices, lessons learned, etc.”

Organizations involved in structural design can benefit from KM by implementing initiatives to develop strategies that help in capturing knowledge that is developed during the different stages of a project lifecycle to make it available and accessible to designers whenever they
require it throughout the organization. Two types of strategy are usually used for managing organizational knowledge: personalization and codification (Sheehan 2000). Personalization supports the transfer of knowledge from one person to another through face-to-face interactions, net-meetings, etc while codification enables the capture and storage of tacit knowledge to make it widely accessible to others through IT and non-IT systems. Given the fragmented nature of the construction industry, it is required to identify what knowledge is to be managed and how to share it. The next section presents a case study investigating some of these issues.

CASE STUDY

The organization employs approximately 175 people in 11 offices around the UK and has an annual turnover of £8m. Its business is construction consulting with more focus on structural engineering design.

STRUCTURAL DESIGN PROCESS

The process of structural design within the organization depends on the type and size of the project being designed. For large projects, the project team consists of members from several offices. The regional manager normally heads the project. The project team includes junior engineers, graduate engineers and technicians. Given the relatively small number of staff within the office, there is always a fair idea of the composition of the team members. The project manager develops the scheme design while graduates and other engineers develop the detailed design.

The organization uses different procurement methods mainly ‘Design and Build’ and ‘Partnering’. It sees partnering as a preferred way of bringing teams together at an early stage. The organization prefers partnering because the knowledge of contractors is brought to the attention of designers at the early stages. This input from contractors was found to influence design. ‘Design and Build’ and ‘Partnering’ also allow the designers to be involved in site supervision and hence improve the learning curve and the transfer of knowledge from construction sites to design offices. This also allows designers to know what clients like and what they don’t like, what contractors can easily do and what is harder to do.

TYPES OF KNOWLEDGE INVOLVED

Both tacit and explicit knowledge are involved in the structural design process within the organization. The way this knowledge is obtained depends on the type of knowledge and its location. During scheme design, most of the strategic decisions are based on tacit knowledge, which, in turn, depends on basic concepts of how the project would be put together and includes fundamental design decisions e.g. whether to use a concrete frame or a steel frame. The organization uses several methods for locating and accessing tacit knowledge. It used a paper database of ‘who knows what’ to locate the tacit knowledge of designers within the company offices. However, paper based ‘expert directories’ tend to be outdated very quickly as staff moved. Emails are also used to locate ‘who knows what’ but are not always found useful. Detailed design is carried out by graduates or other engineers. It involves both tacit and explicit knowledge. Tacit knowledge includes predicting loading conditions, behavior of
structure, etc while explicit knowledge includes codes of design, safety regulations, etc. Tacit knowledge is obtained in the same way identified above while explicit knowledge is obtained through searching the office documents, surfing the Internet, inquiry emails, and knowledge buy-in.

**KNOWLEDGE PROBLEMS**

The organization identifies that structural design is a knowledge-intensive process and that many problems exist regarding how to obtain this knowledge at the time it is required. Most problems are associated with tacit knowledge. Three main problems are identified: obtaining knowledge for new scenarios; consumption of long times to find knowledge; and sharing knowledge between geographically dispersed offices. When designers face a new scenario, the office usually sends an e-mail describing the problem to the other offices and waits for answers. This approach of ‘ask and wait’ dictates that designers could wait for a day or two, possibly longer, to see if valuable knowledge would be received. Designers also recognize that it takes a long time to recall knowledge that is available within the same office especially tacit knowledge. In addition, knowledge gained at construction sites is rarely shared between geographically dispersed offices. Although innovative procurement methods such as ‘Design and Build’ and ‘Partnering’ facilitate more concurrency within the same project, they do not seem to support knowledge sharing across projects as they tend to focus on information/knowledge flow within the individual project being carried out. More sharing is therefore required across projects and between dispersed offices.

**KNOWLEDGE MANAGEMENT STRATEGY AND FUTURE DEVELOPMENT**

The organization does not have a formal way or a strategy for managing its knowledge. However, there are plans to implement some initiatives, which are not necessarily labeled as KM. The knowledge that is of interest to the organization is structural design knowledge. One of the initiatives that the organization is planning to implement is to use the web for information and knowledge sharing. Although the organization is not planning to use an Intranet, they think that using it might come fairly soon. The organization is currently working with technicians in Vietnam where a lot of the drawing work is being done. Communication of information and knowledge between the offices in UK and those in Vietnam take place through e-mails. The organization is also investigating whether an information hub, if based on the web, would be a better way of sharing information and keeping track of what is going on. Although the organization is currently looking at these issues, it does not have a strategy that it would necessarily follow. In fact, the organization is still looking at the different options.

**DISCUSSION**

Structural design knowledge is generated either during the design stage or during the other stages of a project lifecycle. Knowledge developed within the different stages of a project lifecycle requires initiatives that support codifying it and making it available and easily accessible to structural designers. The Egan report (1998) confirms that “designers should work in close collaboration with the other participants in the project process” and that “the
experience of completed projects must be fed into the next one”. The case study indicates that KM could be a powerful approach for supporting collaborative designs not only within a project but also across projects hence allowing concurrent designs in a wider scale.

**Knowledge Problems**

The case study identifies that structural designers face difficulties when they come across a new scenario requiring knowledge to be obtained from other sources. The ‘ask and wait’ approach does not satisfy the requirements of innovative designs. Tacit knowledge is found more critical and hence needs more consideration. This is due to the complex nature of tacit knowledge, the way it is developed, and the process of transferring it to other users. The case study also identifies that the knowledge transfer between construction sites and design offices in ‘design and build’ and ‘partnering’ contracts only give benefits to those involved in the project. What is required is to make this knowledge available and accessible organization-wide. This prevents designers from re-inventing the wheel and from repeating mistakes that were done in other construction projects.

**Potential of KM for CE for Case Study**

In order to help structural designers access the knowledge pools available within the organization or with its partners, a more structured way of managing this knowledge is required. Concurrent design encourages parallel communication and hence supports bringing construction issues to designers at the early stages of design to improve design and reduce numbers of re-design. KM can help in overcoming the knowledge problems identified in the case study through providing a wider meaning of knowledge sharing. First, it supports the sharing of tacit knowledge through initiatives such as Peer-to-Peer interaction, knowledge communities, expert databases, and Groupware (Tsui 2002a). This makes it easier for designers, when they face a new scenario, to locate where the tacit knowledge they require exists, facilitate its communication, and supports its transfer. It also allows the conversion of tacit knowledge to explicit, which can then be saved in a central location (e.g. Intranet) that is accessible to all offices of an organization. This does not only reduce the time required to obtain knowledge but also guarantees that this knowledge is not lost when staff leave the organization. Furthermore, KM supports the sharing of knowledge between geographically dispersed offices using IT tools and systems developed for this purpose (Tsui 2002b).

**Requirements for Implementing KM**

The implementation of KM is not an easy task and requires extensive planning. Two issues are critical when implementing KM: use of proper technology and need for cultural changes within organizations. Although the investigated organization does not have a formal way for managing its knowledge, it identifies that Information Technology (IT) is required for implementing KM initiatives. Intranets and the web technologies are believed to be strong enablers for larger storage capabilities, faster communications, and wider accessibility. Although technology is a potential enabler that supports the implementation of KM in structural engineering design, it cannot achieve the goals of KM unless the whole process of KM is considered. The implementation of the technology part of KM for assisting structural
design should consider several aspects (Garrett and Smith 1996). Firstly, all knowledge needed to perform a given task is not easily acquired or represented. Secondly, structural engineers and construction companies have a strong professional and legal responsibility to society when creating the built environment, and they must be able to understand and make professional assessment of the knowledge used by their computer-aided engineering tools. Thirdly, many structures are “one of a kind”, but engineers can apply components and concepts in one design to other designs; hence, design case bases are extremely valuable. Fourthly, structural lifecycles are measured in decades or centuries. Finally, the context in which the structure must perform is never completely known; engineers and construction companies must manage uncertainty throughout the design and construction processes.

Cultural changes associated with the implementation of KM are the most difficult to address. Most cultural issues revolve around people’s willingness to share their knowledge and availability of time to contribute to the knowledge repository. Structural engineering designers, whether in design offices or in project sites, work under the pressure of fixed deadlines and hence find it difficult to allocate time for knowledge storage. This suggests that organizations need to first make changes to the way staff members behave and interact. Organizations need to allow design team members to be able to communicate closely in all directions and to have the time to access the knowledge available within the organization and to add to it.

CONCLUSION

This paper argues that knowledge management (KM) can provide a potential approach for bringing knowledge to the attention of structural engineering designers at the early stages of design so that more collaborative design is achieved. The management of this knowledge is important in terms of increasing innovation, reducing cost and construction time, and increasing safety. The paper identifies that many efforts have been carried out to improve the structural design process but limited work has been done with regards to managing structural design knowledge. Although expert systems have tried to capture and store the knowledge and expertise of people, they have had a limited impact, as they tend to ignore: the changing context of knowledge; existing organizational cultures; and other human factors. The paper investigated the experience a construction consultant who is heavily involved in structural design and concludes that knowledge management can provide a promising approach for supporting concurrent structural design. However, investigation of more case studies is required in order to truly understand the nature of knowledge associated with structural design and to identify the way forward for managing this knowledge.

REFERENCES


IMPROVING DESIGN FITNESS THROUGH TOLERANCE ANALYSIS AND TOLERANCE ALLOCATION

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ABSTRACT

Stepping back to look at a system and its lifecycle as a whole, it is clear that costs resulting from variability regularly exceed the benefits of more efficient components, processes, and their interfaces within that system. Designers then should pay close attention to how their choices affect variability of the system throughout its lifecycle. A major source of variability often ignored in AEC systems is tolerances. Many problems that manifest themselves during construction and operations are due to a lack of consideration for tolerances in the various components and processes involved in creating civil structures. Application of tolerance visualization can at a minimum allow designers to see the effects of tolerances and thereby enable them to proactively address fixes for a wider range of scenarios, much wider than a single, deterministic one, thus minimizing impacts on process flow. Tolerance allocation tools also may provide a means for achieving concurrent engineering goals by helping to align product design with lifecycle (e.g., construction and maintenance) processes to reduce the overall cost and increase the robustness of the system. Tolerance allocation and visualization increase the opportunity for concurrency by relating two sources of tolerances (variability): design constraints (product) and process capacity (process).

In this paper, 3-D modeling is used to visualize the effects of construction process tolerances on alternative designs for a roof-to-wall connection based on design criteria from a real project. The objective of the paper is to present the potential for tolerance allocation techniques to promote concurrent engineering practice and help generate, evaluate, and select more robust designs.

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INTRODUCTION

A tenet of production management (and particularly of lean production) is to reduce variability (Womack and Jones 1996, Koskela 1992, Schmenner 1993, Taguchi 1999). Variability will take its toll sooner or later in a production process. Examples of costs to be paid due to variability are: long cycle times and high work-in-progress levels; wasted capacity due to low utilization of resources; lost throughput, and a general increase in waste such as poor quality and increased scrap (Hopp and Spearman 1996).

“Tolerance” is a method used to describe variability in a product or production process. It defines the acceptable ranges in the actual performance of a system or its components, across one or more parameters of interest, under the conditions considered during design, for which the system or components are fit for purpose, i.e., meet the specifications and/or customer expectations. Tolerances historically provide the means for communication between product and process designers.

In the 1800s, the move towards interchangeable parts created the need for tolerance representation. Tolerance standards and techniques have been evolving ever since. ASME Y14.5 and 10 ISO standards are governing current dimensioning and tolerancing practices (Voelcker 1997), but researchers in field of tolerances concur that these standards are lacking. Complaints include inadequate mathematical representation of the Y14.5 standard, approaches for analyzing tolerance stacking in complex assemblies (many parts or 3D assemblies), formulas for describing function, and integration of strategies in design and production, and computer tools (Zhang 1997, Houten and Kals 1999, Trabelsi et al. 2000). Due to lack of training (from separating product and process design) and the complexity of the analysis, many times even mechanical designers fail to evaluate the effects of tolerances at component interfaces and on assemblies as a whole. Problems are ‘thrown over the wall’ and left to the shop workers to fix (Henzold 1995, Zhang 1997, Gerth 1997, Houten and Kals 1999). Yet, the concepts and goals of these tools should not be ignored. Researches have made advances in tools to optimize allocation of tolerances to components in a way that minimizes lifecycle cost while maximizing quality (Zhang 1997, Whybrew et al. 1997, Chase et al. 1990, Dong 1997, Dong and Shi 1997).

For the most part, AEC practitioners don’t explicitly acknowledge tolerances in design. They assume that design codes and common practice automatically provide allowances for them. For example, structural engineers in California may argue that the variability in plumbness of an erected structure and the resulting redistribution of loads is immaterial compared to the dynamic loading conditions they consider for seismic design. Of course, codes and common practice provide a minimum standard but they cannot cover all conceivable structures. Not surprisingly, explicit accounting for tolerances is more prevalent in some engineering disciplines than in others. For example, civil engineers do consider variability in the resistance of pile foundations and roundness of large diameter pipe during design calculations and include accommodations in the specifications.

Even when AEC practitioners specify tolerances for components, they seldom consider how these tolerances will interact. This is likely due to industry fragmentation, lack of data on AEC process variability, and lack of tolerance standards or training. Hence the reliance on craftsmanship to deal with changes during construction, show flexibility in applying multiple
or non-standard operations procedures, and remedy problems that could have been avoided by more judicious decision making upstream in the process (e.g., Tsao et al. 2000). Too often, last minute changes result in lower product quality and increased maintenance.

Three strategies exist for dealing with tolerances or variability: (1) reduction of operations variability concerned with the resultant component tolerances, (2) detection and correction of assembly variability concerned with the stacking and interaction of component tolerances, and (3) robustness concerned with allocation of component tolerances (Zhang 1997, Trabelsi et al. 2000). Unfortunately, strategy 1 is limited in AEC, because many building processes are ‘manual’ processes that have large intrinsic variability. Though substantial improvements can be made, there are often substantial limits to reducing the variability both in terms of process time and product precision. Strategy 2 is more promising. Tolerance visualization and analysis provide means to detect and correct for variability in the components or the process (Schultheiss et al. 1999). Even better, strategy 3 is embodied in tolerance allocation and minimizes the impacts of process variability on the rest of the system by aligning or decoupling components and processes through robust interface and component redesign (Howell et al. 1993, Soderberg et al. 1999).

Tolerance analysis views component-related tolerances as a range of values in terms of variation from a nominal value. Tolerance analysis takes a given set of component tolerances, usually based on designer experience or standards, and calculates the resultant variation in the assembly. Through iteration, component tolerances are tightened to meet assembly tolerances, establishing both the product and process design requirements. In contrast, tolerance allocation looks at a range of component designs around a functional or assembly description to absorb the variability. Tolerance allocation is used to maximize quality, minimize production cost, or both. The result can be looser component tolerances and better matching of product and process (Trabelsi et al. 2000, Gerth 1997). Tolerance allocation creates robustness.

Taguchi et al. (1999) define robustness as “The state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in the manufacturing or user’s environment) and aging at the lowest unit manufacturing cost.” They also state that “It is more effective to conduct experimentation at the upstream stage when fewer factors have been decided upon, and design changes are less expensive.” Following this logic, the design phase is the most cost effective time to consider tolerances. Tolerance allocation can even be applied in the conceptual design phase when multiple interfaces can be evaluated for robustness (Soderberg et al. 1999).

To explore issues pertaining to tolerances in AEC system design, this paper examines a connection that, from the first author’s experience, had problems during construction. The connection is used to investigate the application of tolerance visualization, analysis, and synthesis as a means for stimulating concurrent engineering (CE) practice and generating more robust design for a product’s lifecycle.

**EXAMPLE CASE: TUNNEL ROOF-TO-WALL CONNECTION**

The case study looks at the connection between the soldier-pile tremie-concrete slurry wall and the composite steel-and-concrete roof system for a cut-and-cover tunnel construction. Figures 1 and 2 illustrate the connection as designed and executed on this project.
The existing design consists of an erection bracket/seat (arrow ‘a’ in Figure 1) welded to the W36 X 300 soldier pile, a small clip angle (b) welded to the top of the plate roof girder and the face of the pile mostly for stability during erection, and a ⅜” (1.9 cm) bent plate double web cleat (c) which forms the main structural connection. The 60’ to 90’ (18 m to 27 m) roof girders are spanned by stay-in-place (SIP) steel formwork with a reinforced concrete slab on top. Shear studs (not shown) welded to the top of the roof girder transfer loads between the girder and the slab. The roof girders are subjected to the vertical loads of the fill on top of the roof plus the surface traffic, and to the horizontal loads to resist earth pressure on the walls.

CONSTRUCTION (PROCESS) EXECUTION PROBLEMS

Mismatch of Assembly Constraints

A first problem pertained to the soldier pile orientation relative to the tolerances specified in their design. The design allowed for a tolerance of 0.6-degrees of horizontal pile rotation. The piles were to be held in place by resting them against the bottom of the excavation. However, the excavation often went deeper than designed due to poor bedrock, leaving the
piles short of the bottom. Thus, in reality, two piles installed as a connected pair could swing 2 degrees horizontally before hitting the sides of the hole on either side. The design also specified the roof girder to be absolutely (!) plumb. Even if the girder did not have to be plumb there is no guarantee that the pile on the opposite wall was rotated the same direction. With a 2-degree horizontal rotation, for roof girders over 4’ (1.2 m) tall, the problem shown in Figure 3 resulted. The cleat angle does not fit on the pile and cannot accommodate the required ¾” (1.9 cm) fillet weld (a) between the angle and the face of the pile.

The fix was to trim down the clip angle to accommodate the weld, requiring additional engineering calculations, delaying the construction schedule, and increasing inspection requirements. These effects can be viewed as creating additional flow variability in construction, in delays as well as rework, and operations variability in construction, inspection, and maintenance.

**Tight Coupling of Sequential Construction Processes and Manufacturing Steps**

A second problem pertained to the connection tolerance of ¾” to 1½” (1.9 cm to 3.8 cm) between the face of the pile and roof girder. This tightly coupled the manufacturing of the roof to the position of the piles. Detailed survey had to be done and sent to the roof and stay-in-place (SIP) steel formwork fabricators once the face of the pile at the roof elevation was exposed. The roof girder fabricator then required two weeks to make the final cut on the roof to match the pile, paint the end, bend the cleat angles to match the pile, and ship all to site. This ruined much efficiency on site by having to remobilize crews and equipment to an area if and when the girders arrived two weeks later. This also resulted in increased wall movement as the roof girder was part of the wall support. A main concern in the design was to limit wall movement because of the effects on the surrounding buildings. The sensitivity to wall movement also limited the amount of wall that could be exposed at once to take measurements to fabricate the next girders, meaning more delay in all operations.
TOLERANCE VISUALIZATION AND ANALYSIS

Identifying Potential Problems using Tolerance Visualization at Detailed Design

A 3-dimensional (3D) visualization of the assembly showing the tolerance envelopes, the range of possible positions for the connections based on the allowable design tolerances similar to that shown in figure 4 would have revealed these problems (Schultheiss et al. 1999). Current add-ons for mechanical packages such as Sigmund3D (EDS–Ideas) or CETOL6 (PTC-ProEngineer) will perform 2 or 3D assembly analyses while other modules generate kinematic assembly animations (Glancy et al. 1999, SDRC.com 2002).

Although visualization can be timeconsuming because of the amount of data entry required even with new computer aided tolerance tools, it has benefits. At a minimum, the fix for the assembly constraint problem of trimming the angle could have been detected and corrected in the design phase. The procedure could have been added to the specifications, problem piles identified during the contractor survey of the piles, thicker angles used for the cleats and trimmed in the shop. Alternatively, the connection could have been checked: would moving the seat off center allow the cleat angles to fit and remain structurally sound, or could a pile with a wider flange face be used? Such solutions involve redesign of the components and are thus tolerance allocation solutions. In addition, they concurrently design and align the product and assembly process thus avoiding downstream interruptions. Problem two was identified even without visualization and had no identifiable solution given the constraints of the connection.

The tolerance analysis solution and typical reaction to these problems is to tighten the tolerances required for the orientation of the pile. Given tight enough tolerances on pile position, the girders might even be cut in the shop to theoretical length. Regardless of the approach, tolerance visualization helps the designer to identify potential problems in the design phase so that the proper product tolerances are specified and information about potential problems is passed on to those designing the process.

Matching Tolerances to Process Capabilities

Tolerances specified for pile orientations often are much tighter than the process of slurry-wall pile installation can achieve, as shown. So even when designers specify tolerances that accommodate the assembly and connection constraints, the process needs to be checked to ensure it can meet the tolerances. Figure 4 represents the possible orientations of the soldier pile based on the pile installation procedure in yellow. Basing the tolerance analysis on the process capability is a much more appropriate assessment for use in design. Structural design principles dictate that design values are chosen from the worst case 5% of the variability in the distribution of material properties and loads (Holmes and Martin 1983). Accordingly, the tolerance specified in the design should accommodate 95% of the variability in the process capability.

Figure 4 does not illustrate the type of output one might generate for this analysis. More likely it would be an animation of the assembly’s kinematic range of motion. However, the analysis illustrates that the process capability is neither well matched to the design tolerances, nor more broadly to the assembly constraints in this case. With process information, the
analysis triggers the need for CE to match the design tolerances with the process by redesigning one or both. Even better, one might use this information to trigger process improvement or redesign of the assembly concepts, iterating back to systems design level.

**Set-Based Concept Generation and Interface Design at System Level Design**

Alternative assembly/interface options between the wall and the roof were investigated based on a list of conceptual types of connections (Figure 5). All connections are considered until a connection is eliminated due to a project constraint. Looking through the alternatives, only connections C and D pass preliminary evaluation for structural capacity, constructability, operability, etc. Connection A is not feasible because continuity of the soldier pile is required to hold back the soil behind the wall. Connection B is most likely not feasible for the same reason but would require a detailed analysis to be sure. Connection C results in designs similar to the original design (Figure 1). Connection D puts the roof girder adjacent to the piles (Figure 6). This creates additional steps in the slurry wall process because concrete would have to be left out to accommodate and additional design would be needed to transfer the horizontal load between the roof and the pile. However, both these steps seem feasible. Ideally, these alternatives are generated during design at the systems level. Preliminary evaluations must be based on the instinct and expertise of a cross-functional design team including individuals from structural design, contracting, fabrication, operations, and maintenance.

![Connection A: Supported By](image)

![Connection B: Variable Slot](image)

![Connection C: Butt](image)

![Connection D: Lap](image)

Figures 5: Alternative roof to soldier pile assembly concepts

Connections C and D can be checked for tolerance consistency. Consistency here means that the natural availability of the pile installation process is within the assembly constraints of the connection.

**TOLERANCE CONSISTENCY ANALYSIS (VISUALIZATION)**

The tolerance visualization is developed by the constraints of the pile installation process. The piles are hung on chains from a frame that rests on the excavation guide walls. The tops of the piles are a few feet below the ground surface. Concrete is placed through pipes into spaces between the piles. The piles are free and likely to move during concrete placement due to uneven pressures and flow of concrete. The position of the pile is constrained by the chains at the top and the limits of the excavation at the bottom. In the computer visualization, the virtual piles are moved into all possible positions based on the constraints and a solid is generated by the union of these positions. In reality, the excavation is not a perfect rectangle.
nor perfectly plumb. The piles are not straight because they consist of spliced sections that may be misaligned, and steel sections that may not be straight. Further still, after installation the wall bends due to earth pressures. Though possible to include these considerations, we have chosen to ignore the dimensional and form variations in the wall and the piles and focus only on the kinematic variation between the piles and the wall (this highlights the difficulty of modeling actual site conditions). The resultant solids, shown in yellow in figures 4 and 7, represent the process capacity of the pile installation procedure for plumb-ness and orientation of the piles. The distribution of the capacity is assumed to be uniform, i.e., all possible positions are equally likely because of the lack of control in the process.

Unlike manufacturing, process-capability data is often hard to collect in AEC systems as they tend not to be repetitive, as is the case here. Experimental data to determine the actual distribution with alternative processes would not have benefited this job because the pile orientations could not be determined until excavated, which occurs after the walls were mostly complete. However the data could have been used to inform the next slurry wall job. AEC industry might consider means for gathering process data through mockups, virtual production, or sensors for faster feedback. Figure 7 shows the process capacity solid for connection D. The circles show where the piles potentially interfere with the roof girder.

This leads to another decision point on how to proceed: there are three non-exclusive choices for dealing with the lack of consistency.

1. **Process Quality Improvement and Variability Reduction or Component Redesign**

   One could go back and try to redesign the processes to reduce the variability in the process capacity, now given a better understanding of what types of variability have large effects on the assembly. The literature regarding process improvement for all industries including construction is extensive (Kubal 1994, Oglesby et al. 1989, Deming 1982, Juran 1979, Schmenner 1993, and Taguchi 1999). Alternatively, we could redesign a component to avoid the inconsistency like the earlier example, reducing the clip angle leg size and increasing its thickness. Further detail is outside of the scope of this paper.

2. **Modification of the Product Architecture or Sub-system Breakdown**

   One could reconsider earlier design decisions such as the material choice for components thus changing the constraints of the interface design. Ulrich and Eppinger (2000) state that
“The purpose of the product architecture is to define the basic physical building blocks of the product in terms of what they do and what their interfaces are to the rest of the device.” So, from changes in the product architecture a whole new set of interface designs can be generated and evaluated to hopefully find one that is consistent. For example, if the slurry wall above the roof did not serve the added purpose of a retaining wall for construction, connections A and B in figure 5 could be considered. If the wall had been made of reinforced concrete throughout instead of soldier piles, the assembly constraints would change significantly. Though this option has the potential to lead to a more optimal solution, its further pursuit can be very time consuming with no guaranteed results and therefore must be considered carefully along with other project constraints.

3. Detailed Fitness Evaluation Including Tolerance Assembly Reliability

One could measure the reliability of each connection to determine which connection minimized risk. ‘Reliability’ as used here means the probability that the pile position will be consistent with the assembly constraints given the existing pile installation process capabilities. This method has a similar concept to statistical tolerance analysis techniques. Statistical tolerance analysis recognizes that it is not cost effective to design for a stacking interference that will rarely if ever occur. One could then choose the best connection based on the fitness and reliability of the connection and the cost of fix when required. This option provides us with a better understanding of the system and is an effective decision tool when running out of time for further system level exploration.

A theoretical reliability of the connection can be determined by repeating the visualization process while adding the assembly constraint that the cleat angles cannot be less then ¾” (1.9 cm) from the edge of the pile. The resultant solid is the design demand. Again, the distribution is assumed to be uniform. If we then take a cross-section of the process capacity and the design demand at the elevation of the top of the cleat angle (where the additional constraint is located), the ratio of the area of the cross-section of design demand to the area of the cross-section of the process capacity is the reliability of the connection or the likelihood that the pile position will accommodate the roof-to-pile connection.

Similarly, the reliability can be checked for connection D. The dashed red line in Figure 7 shows approximately the design demand for connection D. The choice between the connections cannot be made on the basis of the reliability alone. The different designs and their respective fixes must be evaluated on cost, structural integrity, manufacturability, constructability, operability, and maintainability as well. The advantage of this analysis is that it provides a sense of process reliability when no historical or field data is available. This method is similar to an analysis and decision making tools of Failure Mode and Effect Analysis (FMEA). FMEA is a qualitative approach. “The objective of these analyses is to identify the combination of events that could lead to different degrees of quality and characterize the effects of these different degrees of quality in terms of their potential consequences” (Bea 2002).

Unfortunately, the reliability of connection C and D could not be compared here. Connection C is only unreliable for girder heights greater than 4’ (1.2 m) and information on the number of girders over this height was not available. On the job, there were approximately 10 occurrences of the fit-up problem over 640 connections. Most likely, the
reliabilities are comparable. Connection D did have several advantages including decoupling the roof fabrication from the wall as-built information, increasing standardization of other parts of the roof assembly including the stay-in-place formwork and diaphragms, potentially easier maintenance of the connection, and potentially faster roof installation minimizing wall movement and schedule. However, Connection D also involves significantly more detailed slurry-wall work, additional steel and work to transfer the horizontal load between the roof and the piles, and a lot of excavation support work above the roof elevation. A detailed cost analysis by a cross-functional design team would be required to determine if connection D provides any benefit.

CONCLUSIONS

Tolerance analysis and synthesis techniques encourage CE by acknowledging the relationships between product- and process tolerances. At the component design level, tolerance tools improve robustness by better matching product and process tolerances to avoid downstream problems. Application at the system design level needs further investigation but is recommended. Given the lack of complexity typical in most AEC assemblies and less stringent component constraints than in many mechanical applications, tolerance techniques may prove more immediately beneficial in AEC applications. Table 1 summarizes when tolerance analysis and synthesis techniques are recommended based on the case study presented.

Table 1: Summary of when and why to apply tolerance analysis and synthesis techniques for AEC practice

<table>
<thead>
<tr>
<th>System Design</th>
<th>Component Design</th>
<th>Fabrication</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Capacity Visualization</td>
<td>For process selection</td>
<td>For process selection &amp; improvement</td>
<td>For process selection, problem detection and improvement</td>
</tr>
<tr>
<td>Tolerance Consistency Analysis and Synthesis of Assembly</td>
<td>For assembly process selection</td>
<td>For assembly problem detection and component and spec. redesign for correction</td>
<td>Consistency detection between fabrication tolerances and component design</td>
</tr>
<tr>
<td>Assembly Reliability and Fitness</td>
<td>For assembly process selection</td>
<td>For detailed assembly selection</td>
<td>Selection of component or process if multiple generated in earlier phase</td>
</tr>
</tbody>
</table>

All downstream participants should participate in upstream analyses. Upstream participants are not necessarily needed for downstream analyses. In practice, determining which participants are needed when is an issue of project team design and participant skills, motivation, and incentives.
As for future work, one thought is to find a way to represent other aspects of fitness such as constructability and maintainability in terms of geometric constraints, so that the tolerance analysis can be used to evaluate them as well. Further study of construction and maintenance processes may allow for modeling of these activities in terms of geometric constraints. Ease of constructability and maintainability are often a function of access. Study could provide an association between the shape and size of the area around the connection and grades or levels of access for construction and maintenance. Another thought is to use tolerance analysis for the design of QA/QC. Informed understanding of tolerances may provide a better insight for problem detection. Given the slower nature of construction relative to manufacturing processes there might be opportunity for in-process correction before the problem compounds.

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REFERENCES


PRODUCT INFORMATION MANAGEMENT AT THE LARGE-SCALE PROJECT CALLED ARENA "AUF SCHALKE"

Anke Kamphuis¹, Hennes de Ridder², and Hans Schevers³,⁴

ABSTRACT

This paper focuses on the process of controlling product information during the design and construction phase of the multi-functional large-scale project called Arena "Auf Schalke" (construction time 1998-2001). The arena project is a next generation football and soccer stadium in Gelsenkirchen, Germany. The stadium is not only suitable for football and soccer matches but it can also host other (large) events like pop concerts and theatre productions. The Dutch contractor Hollandse Beton Group (HBG) was responsible for both the design and construction of the arena. In order to control the design process as well as the construction process, the project was decomposed into several smaller components. Decomposition requires coordination. The coordination turned out to be very difficult because an adequate information management system was lacking. For example, it was very difficult to get up-to-date information during the design and construction process. To solve this, a pilot project for information management improvements was initiated within one of the subsystems of the Arena "Auf Schalke" project: the Mechanical and Electrical (M&E) engineering department. This paper is divided into two parts. On part describes the need for information management in this particular project and the other part describes a new information management system, which has been developed, implemented and tested at the M&E department.

KEY WORDS

Design and construct, information management, multi-functional stadium, knowledge management.

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INTRODUCTION

During the early realization phases of the “Auf Schalke” project, controlling the right product (design) information was very difficult. Different versions of documents floated around the organization and the project wide availability of the latest version was almost a project-in-itself. Basically, a good product information management system was lacking. Several aspects fuelled the need for such a system. First of all, the need for information management is in general higher with contract types like Design & Construct and Build-Operate-Transfer (BOT). The contractor needs information about the construction as well as information about the design. Secondly, subsystem managers, -they are called the ‘cluster managers’- expressed their need for information management in order to control their interfaces. Thirdly, the need for information management was a direct result of the multidisciplinary character of the project that demanded a system capable of dealing with discipline specific information. The fourth and last requirement for an information management was based on a strategic decision of HBG. Their idea was to put more effort in an information management system in combination with knowledge management. In this way, HBG expects to be able to re-use the information in similar arena projects in the near future. In the Arena “Auf Schalke” project a simple but very successful information management system (IMS) was introduced. The applied IMS is based on the decomposition of the project and it can even be extended with knowledge management capabilities.

PROJECT DECOMPOSITION

In general, project decomposition is an instrument aiming at (1) simplification of the project by reduction of complexity, (2) stimulating economic rationality by internal specialization and (3) enabling simultaneous work by a number of workers (de Ridder 2002). However, the main problem of project decomposition is a potential loss of overall insight in the behavior of the product as a whole. This means that when a project is decomposed into smaller parts, coordination between these parts is necessary. The more adequate the decomposition, the smoother the coordination can take place” (de Ridder 1994). It is still very difficult to decompose a project in an optimal way. A systematic approach of decomposing a project into smaller parts is subjective to both practical and organizational aspects. Using the ideas of Systems Engineering (SE) several helpful instruments for decomposition can be created (Stevens 2001). In SE, the product is regarded as a system. This system is divided into smaller parts like subsystems, elements, relations, and behaviors. Therefore the product or design needs to be defined to a certain extent.

First, the system is decomposed into elements. Second, relations between those elements are identified (Figure 1). Third, these elements can be grouped based on their interrelations. For design purposes it is helpful to create relatively independent clusters of elements or subsystems. This kind of analyses is also done by means of the design structure Matrix method (DSM).
Products in the Building and Construction Industry are multi-disciplinary. This requires a multi-disciplinary expertise. Every discipline has its own expertise and is only interested in certain aspects of the design. HVAC engineers are interested in HVAC installations, window areas, and energy properties of walls. They are probably less interested in, for example, load bearing properties of a wall. In general, disciplines are interested in certain properties of certain subsystems. In SE, aspect systems refer to the basic issues or topics of a system (Oliver et al.) (and are therefore easy to connect to the different disciplines). For instance, aspect systems like Heating or Maintenance can easily be connected to subsystems.

Again a matrix can be used to visualize the relations between aspect systems and subsystems that can help to decompose the project. However, coordination between the subsystems is still necessary. In consequence coordination between the elements is also necessary. Without proper information, this coordination is very difficult to achieve. Management of information is necessary to assure that the appropriate information is available for the right persons at the right time.

INFORMATION MANAGEMENT IN THE BUILDING AND CONSTRUCTION INDUSTRY

Nowadays, information is probably the most important “construction material” in the Building and Construction (BC) industry (Tolman 1999). Basically, all information gathered about a product (the built object) during its inception, design, construction, use, maintenance,
and disposal needs to be managed. Commercial information management systems like Electronic Document Management Systems (EDMS), Product Data Management (PDM), Object Trees and Product Data Models are available today. Pilot projects introducing the EDM system have been carried out in the BC Industry, for example at a large innovation project of HBG called “Half-time”. This project included a sub project where an EDM system was introduced in a pilot project. A secure infrastructure was created between the project site and the related offices using an extranet environment including among others just simple telephone connections. The EDMS facilitated the storing and retrieving of (CAD) files in such a way that everybody was able to obtain up-to-date files. The package even supported tools for workflow management; with notifications, the correct people were informed of changes, like new CAD files, etc. This kind of information management can have several advantages:

- It allows authorized team members to access all relevant data, at all times, assuring that it is always the latest version
- It can speed up tasks by making data instantly available
- It supports concurrent task management

Another form of information management is the Object Tree approach, which was successfully applied in the “High Speed Railroad Link” (HSL) project in the Netherlands. The Object Tree managed documents like CAD files, governmental documents, but also relations between these documents (Van Nederveen 2000). By analyzing the HSL primary processes, a suitable information structure was created for storing and retrieving documents collaboratively. This information structure decomposes the project information into logical groups of objects. The straightforward decomposition of the information structure is easy and clear. In that way, relations between the objects make interface management easier because relevant information is being clustered. At the end of the project, the object tree system managed CAD files and other documents. More than 2000 objects were being controlled and several hundred users were involved. In the case of the HSL project, object trees were only used to manage information about design artifacts, however the object tree approach is extendible towards management of other information like requirements and decisions. The Object Tree approach is rooted in Product Data Technology (PDT). This is a technology that tries to capture product information in semantically rich (meaningful) objects (i.e., objects like Column, Roof, Wall, etc.) and tries to describe these objects during their whole lifecycle. Furthermore PDT supports the accessibility and logistics of the information and even the representation of the information so it can directly be used in discipline specific software without human intervention. This means that the product data model can be used as input for different applications like CAD, planning software, finite element software, simulation software, etc. Because the model can be used by many computer systems, that could be located in different organizations, the ideal situation would be that these computer systems could automatically access the model. International efforts try to create such an information platform using an emerging product data model for the Architectural/Engineering/Construction (AEC) Industry. This product data model is the work of the International Alliance for Interoperability and is called the Industry Foundation Classes (IFC). Currently, several software implementations are emerging for the AEC industry supporting only a limited part
of information integration. At the moment the focus of these implementations lies on data exchange between different Object Oriented CAD systems capable of supporting objects like “Storey”, “Floor”, “Wall”, “Column”, “Beam”, etc. Several proof-of-concept implementations have been made that are capable of using this information in other software applications like HVAC calculations and planning software (4D CAD). European Research EU projects like COMBINE (http://erg.ucd.ie/combine.html) and CONCUR (http://cic.vtt.fi/projects/concur/main.html) have been working on an integration platform for project information, which is perhaps the highest level of information management. In the BC industry however, more simple Product Data Management systems like EDMS and Object Management are not widely spread.

INFORMATION MANAGEMENT DESIGNED TO SUPPORT COORDINATION

For full support of the product information management needed for coordination, it is necessary that the information management system include the same aspect systems, subsystems and relations as the project. Furthermore the information management system must be able to present the product information in the same structure as the decomposition of the project. With this approach, product information can be stored and structured in one system for the entire organization. For example, design information like requirements and design decisions can be stored in such an information system. The information structure is known and accepted by the organization. This makes the system extremely useful for the entire organization.

Only product related information is stored. This means that the information management system uses subsystems for example physical parts of the design like ‘Foundation’ ‘Sliding pitch’, ‘Roof’, ‘Finishing of the Arena’ etc. Design information related to one or more subsystems must be related to these subsystems in the information management system.

Aspect systems are used to describe certain functions of the system like “ventilation system” or “hydrological system”. Relations can be used to define subsystems, which are involved in aspect systems. For example, the aspect “Ventilation” is interrelated with several subsystems like ‘the arena hall’, ‘roof’ and ‘finishing of the building’, etc. Disciplines involved in the “Ventilation” aspect, are only interested in the subsystems connected to this aspect element. A matrix is formed by the identified subsystems and the identified aspect systems. This matrix contains all design information that is by definition related to subsystems and aspect systems.

In a prototype implementation, this matrix formed the basis for information management system (Figure 3) for requirements. In this prototype, a tree is used to display physical subsystems. Another tree is used to display the aspect systems. Selecting a subsystem and an aspect system, a requirements matrix is generated dynamically. The decomposition of the selected subsystem and the decomposition of the selected aspect system are forming a matrix. In every (empty) cell of this matrix which is by definition related to a subsystem and to an aspect system, requirements can be inserted that are also related to both subsystem and aspect system.
During early phases of design processes, the propagation and behavior of all subsystems and all aspect systems probably won’t be available or will only be available at a high level of abstraction. This means that subsystems and aspect systems are only described at a certain level of abstraction. Therefore, the content of the matrix has to contain the same level of abstraction as the status of the project. This implies that the abstraction level of the content of the matrix must be in line with the abstraction level of the design process. Early design phases, requirements and decisions are made at a high level of abstraction, for example, requirements stating the amount of people that a multi-functional stadium should be able to house. In the matrix this requirement would be related to a high-level physical subsystem like Arena, and would be related to an abstract aspect system like “Spatial/Housing System”. In later design phases, this requirement will probably be redefined into several other requirements like the amount of seats, number of toilets, etc. During the design process both the requirements as well as the subsystems and aspect systems will be refined and completed. For example, the aspect system “climate system” could be decomposed into other aspect systems like “heating system”, “cooling system”, “ventilation system” etc. Supporting this process, the information management system must be capable of creating new subsystems and new aspect systems that result in new cells for new requirements. This idea of information management is implemented in a research project at Delft University of Technology (Figure 3) (Scheyers and Tolman 1999). Product information gathered during design processes can be easily stored in the system, keeping up with the abstraction level of the product.

ARENA “AUF SCHALKE” CASE

INTRODUCTION

HBG as a main contractor has considerable experience with the construction of modern multifunctional football/soccer arenas, like the Arena “Auf Schalke”. HBG has proven a
track record with similar projects like the redevelopment of ‘de Kuip’ in Rotterdam, the ‘Philips stadium’ in Eindhoven, the Parkstad Limburg Stadium of FC Roda JC in Kerkrade and the new stadium ‘Gelredome’ in Arnhem (all Dutch projects). HBG awarded the Design & Construct contract to realize the “Auf Schalke” project in Gelsenkirchen (Germany) within thirty-four months.

Figure 4 shows the new home stadium of football club “Schalke 04” which can also host other large events like pop concerts and theatre productions. This project was HBG’s first
project in Germany and it was also considered the first one in a series of ambitious projects in the near future. The project was decomposed into components that needed interface management. Since HBG was very eager to re-use information and knowledge gained in this project, therefore a pilot project was initiated to improve information management.

**DECOMPOSITION OF THE “AUF SCHALKE” PROJECT**

The Arena “Auf Schalke” is a multifunctional Arena defined by many requirements. The design and construct contract was a constraint to achieve an adequate decomposition (Kamphuis 2001). The main dilemma was whether or not to decompose the project in many highly manageable parts, which would heavily interrelate, or to decompose the project in fewer complex parts. The project management decided to divide the Arena “Auf Schalke” project in a relatively simple way into seventeen smaller “projects” (Figure 4), which would interrelate heavily. This decomposition method induced a lot of coordination, due to the large amount of interrelations between the clusters. Relations were identified and cluster managers were appointed to control the interfaces between the sub components. The cluster managers were responsible for the coordination and communication between two or more sub components. They needed up-to-date information about all the components that were interrelated, which in fact contained all requirements and design decisions related to the sub components. Adequate controlling was only possible with an information system, which allowed them to easily access up-to-date information of other components.

**Figure 4: Organizational structure of project Arena “Auf Schalke” (project management) and decomposition of the system (system approach) are integrated**

**SOLUTION: PRACTICAL INFORMATION MANAGEMENT SYSTEM**

The main focus of the approved information system was to handle design information in the same way as the requirements. The design solutions and design decisions also had to be handled this way. The primary goal of the system was to provide the cluster managers
appropriate up-to-date information. A simple information management system was developed and directly implemented at the “Auf Schalke” project within the Mechanical Engineering and Electrical Engineering (M&E) departments. Basically, subsystems and aspect systems were used to create a matrix (Figure 5).

Figure 5a: Information matrix: the decomposition of the sub system mechanical and electrical engineering: a two-dimensional graphical representation of relations between sub systems and aspect systems.

<table>
<thead>
<tr>
<th>A Business club</th>
<th>B Promenade</th>
<th>M Technical room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect (sub) System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Heating installation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan Coil Units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter temperature: -12°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5b: One cell of the information matrix: the element ‘Heating’ (2.1) and aspect-system ‘Kiosk’ (B1): the information of one aspect system is input from different levels and phases in the process (bill of requirements, meetings between the client and the contractor and internal meetings of HBG).

The cells of the matrix represent relations between subsystems and aspect systems. These cells can be used to store extra information about these relations. In the arena project, the cells were used to store information like requirements and design decisions (Figure 5). Basically, this structure is capable of capturing all requirements, all design decisions, and all other information. The matrix organizes these design decisions and requirements by use of
product decomposition and aspect systems. The search for information (requirements and design decisions) then becomes easy when you know in which aspect system or subsystem the information is located. On the other hand, structuring the information using the subsystem and aspect system approach prevents disciplines from over-consumption of information. Furthermore, when design decisions related to physical subsystems are made, the matrix facilitates communication about this decision to all other disciplines related to these physical subsystems.

RESULTS OF APPLIED INFORMATION MANAGEMENT SYSTEM

In general, the information management system provides a means for cluster managers to find the appropriate information easily. This is a strong tool for coordination of subsystems. The system offers an information structure for all requirements and all design decisions. Full benefit of the information management system can be obtained by bringing the information up-to-date. The managers of the subsystems were responsible for keeping the information management system up-to-date. In practice however they failed. M&E engineers claimed, that they did not have enough time to update the information management system. Furthermore, the system was new and thus not embedded at M&E engineering because the information system did not carry direct advantages for the M&E engineers. The priority to keep the system up-to-date was low.

Another result of the use of the matrix was that the matrix became a checklist. The matrix not only gave an overview of the requirements but it also provided an overview of white areas in the matrix (lack of requirements on certain aspect elements and subsystems). Having identified these areas, it became easier to check whether certain requirements or other information were missing or not.

FUTURE DEVELOPMENT

INTRODUCTION

The applied information management system was nothing more than an excel sheet containing the matrix and the product information. At every meeting, this excel sheet was used and new information was entered by one person. Using (standard) Information and Communication Technology, several advantages can be achieved: improved scalability, accessibility through Internet, multi-users access, tracking of changes (who changed what and when), read/write rights, etc. Most of these functions are present in available commercial Product Data Management software. The current approach of information management can be extended to serve different purposes. For example, the same matrix approach can be used for capturing information during the whole project starting from the beginning. The matrix can also be used as an instrument for project decomposition. Identifying the relations between aspects and subsystems provides an overview of interrelations. The matrix severs as a tool to provide insights into the way a project could be decomposed. The strategy is to minimize the interrelations. Another possibility for extending the current system is to store the information in such a way that it becomes re-usable in other projects. In this case, the contents of the information management system serve as knowledge for other projects. The following paragraphs describe these possible extensions of the applied information system.
PROJECT DECOMPOSITION SUPPORT

By using the proposed information management system at the beginning of a project, relations between subsystems and aspect systems can be directly identified and can thus be used for insight on interrelations. When representing the information within the cells by dots, a figure like figure 1 can be generated automatically showing the interrelations between subsystems. Figure 2 shows the relations between subsystems and aspect systems. When considering only one aspectsystem, related subsystems can be found easily.

KNOWLEDGE MANAGEMENT

Using the applied information management system for future projects, it can be extended to store the information of multiple projects. Each cell in the matrix can be re-used, if the aspect system and subsystem are available. This means historic information in that particular cell can be accessed and re-used. For example, the system can retrieve historic requirements and adapt them for future projects. Because every requirement is linked to subsystems and aspect systems, the system can provide historic requirements on this specific subject. In the prototype implementation of the requirements desktop (Figure 3), requirements are stored in a database and can be retrieved at any time.

CONCLUSIONS

The matrix of the information management system connects subsystems to aspect systems. The cells can be used to store all requirements and all design decisions that are related to both the subsystem and the aspect system. This approach was adopted at the mechanical and electrical engineering department of the Arena “Auf Schalke” project and proved to be useful for interface management. The cluster managers could easily access relevant and up-to-date information about their clusters. This facilitated the management of the interfaces between these clusters. The simplicity of the system made it easy to adopt it. However, the priority of using this system was not high for mono-disciplined workers. This resulted in slow up-dates of the system. It is necessary that workers understand the importance of the system. This can be difficult when workers do not see direct advantages for themselves. Except for this cultural problem, the general opinion of the people, who used it, was very positive. Because all requirements were grouped it became easy to get a complete list of all relevant requirements. Furthermore, the information management system became a support tool for the cluster managers who needed up-to-date information about more than one cluster. Because the information management system is generic, it could be useful in other complex projects (e.g. the construction of a high-speed railways and complex real estate buildings). Hopefully less embedding problems will occur when introducing this information management at the start of a future project. It is expected that this type of information management will have a positive effect on efficiency and costs.

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REFERENCES


IFC (--). Industry Foundation Classes by the International Alliance for Interoperability, http://iaiweb.lbl.gov/


