Goals, Dimensions, and Approaches for Computer Integrated Construction

M FISCHER[1]
M BETTS[2]
M HANNUS[3]
Y YAMAZAKI[4]
J LAITINEN[5]

ABSTRACT

The recent years have seen significant research in the area of computer-integrated construction (CIC). CIC research has been largely technology driven and is usually seen as good per se. Researchers often neglect to describe the expected engineering impact of the solution they propose and typically fail to test how well the developed solution addresses particular problems of industry or whether any such problem is being faced. An important reason for this, we argue, is that we still lack an overall vision for the goals of CIC and are missing a unifying framework that defines CIC and its application in the engineering context. Furthermore, CIC research has been surprisingly fragmented. This paper proposes a framework that measures several main dimensions of CIC. The purpose of this framework is to assess the current state of CIC in particular firms, to provide a focus for research and implementation of CIC, and to position and compare different research projects.

Key Words
information technology; integration; automation; computer integrated construction; engineering process

INTRODUCTION

The architecture-engineering-construction (AEC) industry has been unable to significantly improve its cost effectiveness (Business

1 *Assistant Professor, Construction Engineering and Management Program, Department of Civil Engineering, Stanford University, Stanford, CA 94305-4020, USA.*
2 *Department of Surveying, University of Salford, Salford, M5 4WT.*
3 *Laboratory of Structural Engineering, Technical Research Center of Finland, PO Box 26, 02151 Espoo, Finland.*
4 *Manager, Intelligent Engineering Systems, Technology Division, Shimizu Corporation, No.1- 2-3, Shibaura, Minato-ku, Tokyo 105-07, Japan.*
5 *Development Department, Haka Oy, Innopoli, Tekniikantie 12, 02150 Espoo, Finland.*

Roundtable, 1983). If the AEC industry was able to deliver projects of higher quality faster and cheaper it might stimulate the construction of many facilities worldwide and improve the infrastructure that forms the basis for many other businesses. Unfortunately, the current project delivery process is unlikely to produce the order of magnitude increases in efficiency required for this task, and current research is too fragmented and lacking an overall vision or strategy to provide much help either.

The need to adopt a visionary or strategic perspective to business operations has been recognized in other sectors of the economy for over two decades. As Betts and Ofori have observed (1992) the economic and business planning frameworks and priorities have shifted from the short-term and tactical to the long-term and strategic. Production management in other industries is becoming revolutionized by emerging techniques such as just-in-time resource management and total quality management. These have been combined as a new production philosophy (Womack et al, 1990) which Koskela (1992) has applied to construction.

Thus, in summary, one can observe a strategic shift in the emphasis of business planning from internal to external concerns with such criteria as value and competition in global markets becoming more important that financial returns. Enterprises in many sectors have realized that they must do more than react to events, and are endeavouring to influence the future, at least with respect to their operations. It is in this context that we should examine opportunities for CIC.

Industry Problems: Ineffectiveness of the Traditional Engineering Process

Project-based industries have been slower in adopting many of the new management, production and competition philosophies described above. This is explained by the one of a kind nature of the process and product, the fragmented industry organization and the low level of investment in and exploitation of technology. As a consequence, many construction projects are poorly managed at the critical early design stage.

We can illustrate this argument with an often used diagrammatic representation of the classic construction problem. Figure 1 depicts the two S-curves of a typical construction project (Ahuja and Walsh 1983, Ferry and Brandon 1992). Traditionally, the increasing S-curve represents the amount of resources spent and the decreasing S-curve shows that the amount of resources that can still be controlled gets smaller as the project advances. These curves are generally used to point out that owners spend little money at the beginning of a project to make important decisions.

We propose to re-interpret these curves in the following way: the increasing S-curve now represents the amount of information developed by project participants over the course of the project, and the decreasing S-curve represents the impact of decisions on the overall project. One quickly notices that we make important decisions with little information and as our understanding of the project increases the importance of the decisions decreases. The curves are purely qualitative, *ie*, we don't imply that the amount of information generated in the maintenance phase is necessarily smaller than in the construction planning phase. Today, a typical construction project begins with a handful of professionals developing initial project data to support important early decisions regarding the viability and size of a project. Throughout the project, the number of participants and the amount of information available to support decisions increase constantly. At the same time, the significance of the decisions in the overall project context decreases steadily. This basic problem in the traditional engineering process—basing important early project decisions on little data—is compounded by the fragmentation of the architecture-engineering-construction (AEC) industry. This fragmentation further increases the likelihood that early decisions have a negative impact on downstream disciplines.

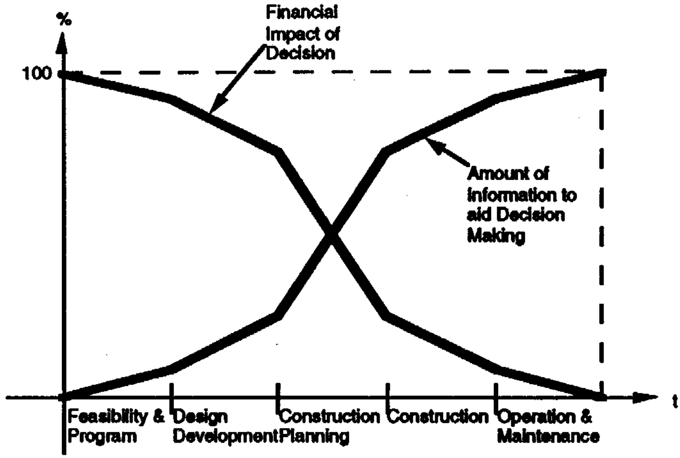


Figure 1. Decisions and Information in the Traditional Engineering Process

Furthermore, initial project development is often slow. It can take several months to develop a project to a point that would allow a well-founded decision. Thus, the number of well-developed alternatives is very small. In our experience, project participants are usually not willing (and do not have the budget) to change an earlier decision if a later evaluation, indicates that the chosen alternative is not as good as it could be. This lack of experimentation during early project development is compounded by the fact that owners often change project requirements as the project evolves because benefits of a potential solution become clear only at a later stage.

The construction industry has responded to these challenges by bringing more disciplines into a project earlier and by fast-tracking the schedule. These solutions do not come cheap. It takes many years and perhaps mistakes to become an expert, it is expensive to have many potential project participants attend all project meetings, and fast track schedules are not always fast and often increase costs.

It appears that, if project data and alternatives could be developed more rapidly, the problems described above could be eliminated or their effects reduced. As we will show below, CIC is a major strategy to achieve this goal and to overcome these problems.

Research Problems: Fragmentation and Technology Fascination of Integration Research

There has been a major shift in the way business perceives information technology (IT), with inter-organizational systems as part of greater integration efforts being a central theme. Yet, of all the predictions that were made for IT advances in the 1980's, inter-functional integration has proved the most difficult to achieve for organizational rather than technological reasons (Benjamin and Blunt, 1992). Recent years have also seen a significant increase in integration research in construction. Many construction professionals and researchers have come to realize that the current fragmentation and specialization in the AEC industry lead to significant problems, such as a construction scope larger than necessary and missed opportunities for advantageous construction methods (Tatum, 1987) to name just a few related to the design-construction interface. Research has generally focused on technology that would allow project participants to share data, in particular between upstream design activities and downstream construction activities and that would make downstream construction knowledge available in upstream design phases.

The first type of integration—data integration—includes efforts tying together existing software tools, approaches to facilitate data sharing through an intelligent database interpreter, shared product and process models, and agent-based programming to model the data needs of various disciplines and project participants. All of these approaches offer the opportunity to speed up the development of project data because they reduce the amount of re-interpretation currently necessary when transferring data from discipline to discipline and from phase to phase. However, improved electronic data sharing does not necessarily alter the engineering processes in a significant way to generate additional value for customers. The main research challenges have been the different data needs and views of various disciplines during different phases and the lack of standardization within a given AEC discipline.

Research for the second type of integration—heuristic integration—has mainly focused on providing knowledge about "ilities" (constructibility, operability, maintainability, etc) to designers. Typically, this type of knowledge consists of heuristics, and reasoning is based on a limited model of the design product. However, the amount of heuristics required to mimic the experience of professional experts is—at best—very large and difficult to maintain. Furthermore, research projects have typically focused on the integration of two phases or disciplines only, and there are no proposed solutions to the integration of heuristics from various domains. With respect to the information S-curve in Figure 1, heuristic integration shifts the information curve upwards, *ie*, it allows project participants to make decisions from a higher state of knowledge which should improve the quality of decisions.

Researchers do not always justify their research based on problems in engineering practice. Often, the purpose of integration research in an engineering sense is ill-defined and research results are not tested regarding how well the proposed solution helps to overcome an engineering problem. Thus, integration research has produced many solutions looking for real world problems *ie*, most integration research provides a technology push. An alternative approach that has gained much acceptance in management disciplines is to follow research and development in support of a strategy pull. A number of writers have commented on how companies can exploit technology to gain strategic advantages (Porter and Millar 1985, Earl 1989, Daniels 1991). Earl in particular stresses the need for the 'technology strategy connection' to be made and advocates the use of planning frameworks to assist in this. This is addressing the organizational issue.

In addition, most research projects are isolated short-term efforts. This temporal fragmentation has led to many ideas that have been developed to the prototype level but have typically been abandoned before being tested in a practical engineering context.

Furthermore, researchers generally bemoan the lack of standardization in the AEC industry (Fischer and Froese, 1992), but have themselves done little to agree on a standard terminology for integration research. For example, there exists no generally accepted definition of the word integration in the context of CIC. Researchers at the Center for Integrated Facility Engineering (CIFE) have defined integration as "the continuous interdisciplinary sharing of data, knowledge, and goals among project participants" (Fischer, 1989).

VISION FOR CIC

If we had the option we would like to make project decisions from the position indicated by the black dot in Figure 2. We would like to have all the project information that we could wish for available instantly. This is likely to remain a dream, but nevertheless indicates the direction in which we should try to push the information curve: back and up. The information curve can be pushed back and up in just one phase or in several phases at the same time. Two key concepts will allow us to achieve these goals of CIC: integration and automation. Integration and its effects on the traditional engineering process have been described above. When coupled with automation, we foresee significant savings in the time required to develop project information.

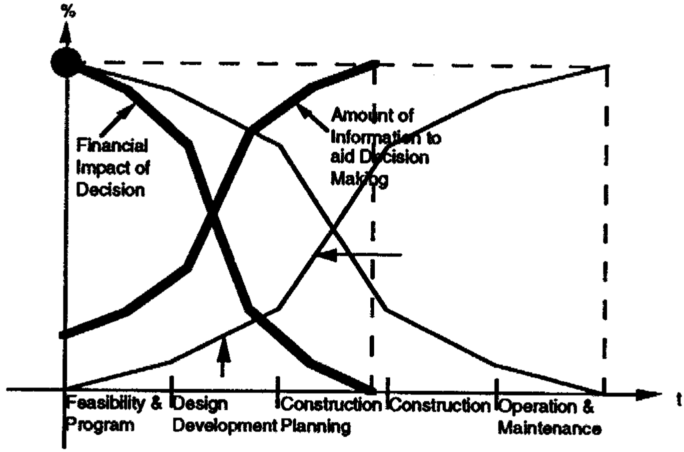


Figure 2. Impact of CIC

We propose to symbolize integration and automation with a circle (Figure 3). The circle shows not only the sharing of project data among project disciplines—a reason for integration in itself—but also the potential for the automation of engineering tasks in each of these phases. While one can expect improvements in the quality of decisions and reductions in design and construction duration, integration alone is not likely to cause the increases in quality and efficiency necessary to create and satisfy the demand in construction over the next decades. We should attempt to approach the black dot in Figure 2 as much as possible. This can only happen with a significant increase in automation of individual engineering tasks. Much of this has been happening in AEC offices around the world over the last two decades in the form of islands of automation. Sharing project models now allows us to tie all these applications together and develop project data much more rapidly. It has been recognized that automating traditional processes is a poor strategy to create value adding processes with new technologies (Hammer, 1990). Thus, we propose a goal of going around the circle—*ie*, completing the virtual design, construction, and operation of a facility in as short a time as possible—in about one minute. Such a goal should provide the impetus to redesign, formalize, and automate engineering processes to take advantage of the fast, cheap hardware available in the future.

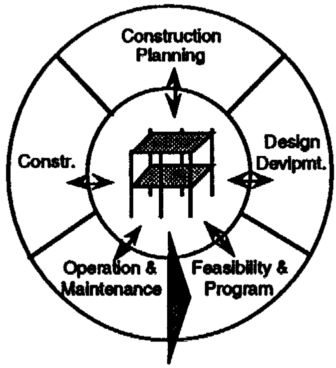


Figure 3. Automation and Integration: Two Key Concepts of CIC

Such tools would enable professionals to explore many more alternatives than they can today, to experiment with various requirements and solutions, to demonstrate the impact of a decision in one discipline and phase on other phases, disciplines, and the overall project. Moreover, such tools would be learning and communication tools because the impact of decisions could be shown almost immediately during meetings. This should lead to faster decisions and agreements. If we contrast this with the slow, week to week, or month to month development and evaluation of ideas custom to today's projects we realize that such an automated and integrated project development tool does not only offer the potential to improve the efficiency of the project delivery process dramatically but is an absolute necessity for competitive facility development in the future. Instead of using computers to help manage the complexity of projects, CIC will use computers to simplify complexity. This is central to the theme of the new production philosophy (Womack et al, 1990). Decisions that were once irreversible will become reversible. Figure 4 shows the effects of achieving this level of integration and automation. Project development time has been reduced significantly and project quality is likely to be better too because more alternatives have been explored in enough depth to allow a true evaluation of project requirements and corresponding solutions.

Figure 5 shows various options and stages of automation and integration that we envision. One could imagine an approach of automating current discrete activities without sharing a common project model (a). Such an

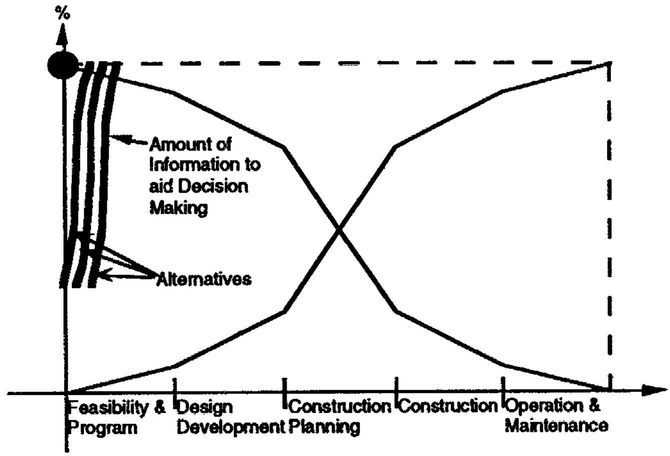
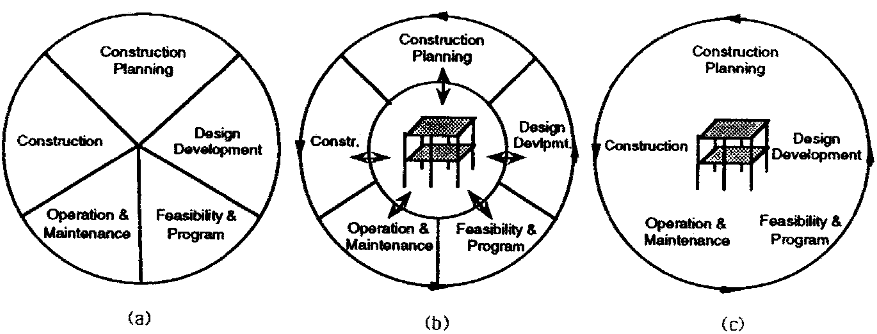


Figure 4. Impact of Automation and Integration

approach would, however, require a significant number of linked applications and is not thought to be effective for the multitude of applications present in the AEC industry (Fischer and Froese, 1992). The two other circles show varying degrees of sharing data among applications, phases, and disciplines. In a first step, a few applications would share and reuse some data (b). In later steps, the sharing and processing of all project data would be integrated for many applications, disciplines, and phases (c). This may represent the ultimate solution for CIC.



(a) (b) (c)

Figure 5. Several Options and Stages of Automation and Integration

We offer these goals of integration and automation as a vision for focused development and implementation efforts. They also offer the opportunity for the continuous improvement necessary to the success of CIC. They provide some answers to the question of what integration should achieve.

CIC FRAMEWORK

The CIFE definition of integration prompted us to ask several questions regarding CIC. We started to wonder who integrates what, how and when one should integrate, and why one would choose to integrate. This led to the development of the framework presented in Table 1. We would like to propose this framework as an initial basis for discussion to define dimensions and levels of integration towards CIC.

	(1) -> Low Integration	(2) ->	(3) ->	(4) ->	-> (5) High Integration
Who?	Individuals	Depts.	Entire Org., Firm	Whole Project Life Cycle	Entire Industry
What?	Data	Models	Knowledge	Goals	All Project Information
When?	Islands of Automation	Multiple Apps in one Discipline and Phase	Multiple Apps from several Discipl. in one Phase	Multiple Apps from several Disciplines and Phases	All Apps in Project Delivery Process
Why?	Survive, Stay in Business	Increase Profit	Increase Market Share	Enter New Market	Create New Market

Table 1: Dimensions and Levels of Integration

With regard to who, we can imagine integration among individuals and departments leading to the integration of entire firms and projects and ultimately to the integration of the entire AEC industry. Regarding the question of what to integrate, as an initial step we might choose to focus on sharing just data electronically which is already done on some projects today (Architecture, 1992). This could then be expanded to include models, such as product and process models, knowledge about decisions, and project goals. Ultimately, data, models, knowledge, and goals would all be shared. With regard to when to integrate, just a few applications within one phase and discipline might be a starting point which then could be expanded to include all applications from all disciplines and phases. Reasons for integrating or increasing the level of integration are to stay in business, increase profit, market share, market size, or to enter or even create new markets. The "why" dimension could also be adjusted to include other typical project objectives such as schedule, quality, and safety. That CIC offers these opportunities has already been demonstrated by such companies as OTIS (Cash and McFarlan, 1990). Daniels (1991) also reports of a building materials supplier exploiting similar opportunities.

This framework allows individuals, departments, companies, projects, and industries to plot their current state of integration and to indicate efforts to increase the level of integration. Thus, the framework becomes a vehicle for comparison and for focusing development and implementation efforts. For example, two departments might differ in their capabilities of sharing project information, or a company might be interested in pushing its integration capabilities from level 3 to level 4 for the 'what' dimension.

This framework also provides generic and focused definitions of integration. Generically, integration can be defined as the sharing of something by somebody using some approach for some purpose. Obviously this is not a very useful definition. However, if one substitutes the vague expressions with values from the framework one can create a definition that suits a particular purpose. For example, a firm might define integration as the sharing of data and models by departments using several applications pertaining to a number of disciplines and project phases to increase profit and market share. Another company might define integration differently because it has a different purpose or image. The advantage of the framework is that it relates different focused definitions.

CONCLUSIONS

In this paper, we have outlined current problems in AEC practice and research. We argued that CIC provides the focus and the means to overcome these problems. We presented a vision for CIC and proposed an initial unifying framework to define integration, to measure levels of integration, and to focus development and implementation efforts. Today, professionals spend a substantial amount of their time applying their knowledge, *ie*, analyzing a problem, formulating a solution, and evaluating the solution with respect to requirements defined in the analysis stage. In the future, CIC will automate and integrate much of the application of at least the knowledge required for evaluation. This means that companies and individuals will expend fewer resources applying what they know and will be able to synthesize solutions faster. They will rather have to focus on creating, formalizing, and maintaining their core business knowledge so that it can be applied automatically. A construction company will have to become a R&D company in construction because it will continuously have to learn and update its knowledge bases (Applegate et al 1988, Laitinen 1992). Figure 6 exemplifies this change in project execution. Each project is seen as a learning experience that updates and refines a firm's knowledge base. Therefore, each new project is started from a higher state of knowledge, and the automatic application of knowledge is likely to be faster too. This is of course exactly what happens at present in an unstructured and manual way. The benefits from CIC will come from the discipline given to this activity and the formal and structured way the knowledge would be recorded. Thus, CIC will provide the focus and the means for construction professionals to attain continuous improvements of the project delivery process. This vision is similar to the management and production philosophies outlined earlier.

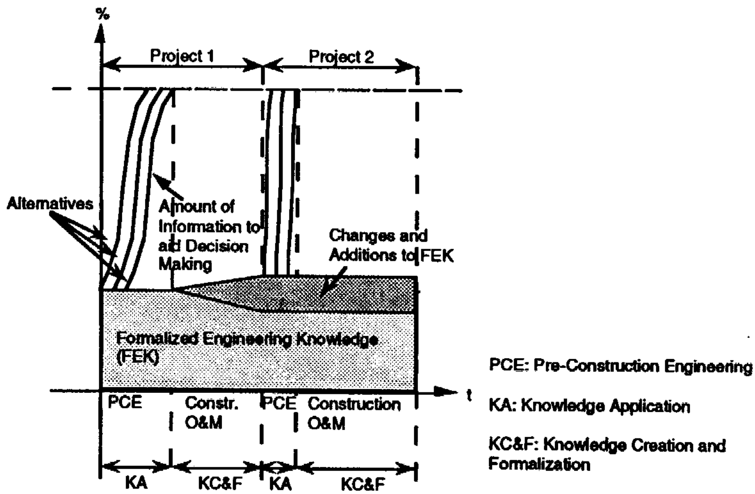


Figure 6. Impact of CIC on Project Delivery Process

Integrating the three intellectual activities of practice, education, and research — or in other words on the application, dissemination, and creation of knowledge - is probably the biggest impact CIC will have on the lives of AEC professionals.

ACKNOWLEDGMENTS

We developed the material presented in this paper at the International Workshop on Models for Computer Integrated Construction in Espoo, Finland from October 5-9, 1992. We would like to express our gratitude to VTT for sponsoring the workshop and thank the other participants (Bo-Christer Bjork, Grahame Cooper, Thomas Froese, Richard Junge, Kari Karstila, Bart Luiten, and Rivka Oxman) for their insight to the content of this paper. We also thank Jim Breuer and Paul Teicholz for their reviews of an early version of this paper.

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