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Computer Integrated Construction

Intégration de l'ordinateur dans le processus de la construction

Zur Integration des Computers in den Bauprozess

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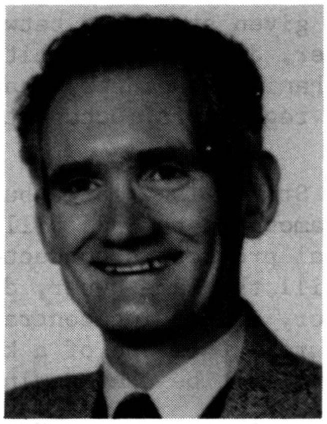

Richard Wright, born 1932, received his Ph.D. in civil engineering from the University of Illinois, Urbana, Illinois, where he served on the faculty from 1957 – 1974. Since 1974 he has been director of the Center for Building at the U.S. National Bureau of Standards.

SUMMARY
Computer integrated construction denotes a system for the automatic exchange of information between participants and devices in the construction process throughout the project life cycle (design to construction to end use). A principal requirement is that open systems of software and hardware are needed by the nature of the U.S. construction industry for successful automation in the construction project.

RÉSUMÉ
L'intégration de l'ordinateur dans le processus de la construction permet un échange automatique de l'information entre les participants et les systèmes concernés par le processus de la construction, de la conception à l'exploitation de la construction. Une condition essentielle pour le succès de cette automatisation est que des systèmes évolutifs de matériels et de logiciels soient mis à disposition.

ZUSAMMENFASSUNG
Die Probleme des automatisierten Austauschs von Informationen zwischen den am Bauprozess beteiligten Personen und Geräten vom Beginn der Planung bis hin zur Nutzung des Bauwerks werden beschrieben und geeignete Lösungswege aufgezeigt. Eine wichtige Voraussetzung für den Erfolg dieser Automatisierung ist, dass «offene Systeme» für Software und Hardware zur Verfügung stehen.

1. INTRODUCTION

Computer integrated construction is an approach to the application of advanced computation and automation throughout the construction process. The construction process encompasses the whole life cycle of the constructed project. The stages include, among others: programming to define requirements for the project, preliminary design to identify the concepts and schemes for the various physical systems of the constructed facility, detailed design to develop plans and specifications, site construction activities, use and maintenance of the facility, and removal or renovation. Computer integrated construction includes information flow between the various participants in the construction process, at a given stage and between stages. The participants include, among others: owner, developer, architect, structural engineeer, geotechnical engineer, mechanical engineer, manufacturers of products, general and specialty contractors, regulators, occupants, operators and maintenance personnel.

Construction in the United States is a large but disaggregated industry. In 1986 [1] new construction amounted to $375 billion, 8.9% of the gross national product. However, the usual project is conducted by a unique team. Never before, and never again, will the same owner, developer, architect, structural engineer, general contractor, concreting contractor, etc., work on the same project. Also, the usual project is one of a kind. The design, construction method, equipment, etc., will not be used again on another site.

Automation and advanced computation must be used by the various participants in the construction project if they are to be competitive in the marketplace [2]. Each must procure and become skillful in the use of his own computational hardware and software and automated devices. Because the construction team is unique to each project, open systems are needed for automatic exchange of information between participants [3]. It is infeasible to require participants to purchase and learn to use a single system of hardware and software. Because the construction team is unique to each project, and because capital is scarce and capital investment is risky, automated construction devices, whether design equipment or robots at the construction site, must be usable in association with an arbitrary mix of manual and automated technologies [4].

Automation of the constructed facility will be necessary to meet owners' and users' needs for efficient and productive facilities. Again, open systems are required in the hardware and software of an automated facility [5]. In an open system, each component has well defined characteristics for information input and output, and for performance. An owner can consider alternative suppliers for components of the initial system, mix manual and automatic functions, and upgrade the system incrementally as technologies and needs evolve.

This paper presents a scenario for the effective introduction of advanced computation and automation into the construction enterprise. Principal aspects are: integrated computer-aided design, automation on the construction site, and automated facilities. The principal common feature stimulating cost-effective, incremental introduction of automation is the use of open systems of hardware and software to promote incremental automation and to allow the simultaneous use of arbitrary mixes of automated and manual techniques. The National Bureau of Standards (NBS) supports the development of computer integrated construction through research for information interface technologies, performance prediction methods, measurement methods and test methods needed for open systems of construction hardware and software.

2. INFORMATION INTERFACES FOR COMPUTER AIDED DESIGN

2.1 Integrated Project Information System

The integrated project information system provides a dynamic repository for project specific information that can be appropriately accessible to all project participants. The Building Research Board [6] has been studying the development of integrated project information systems and demonstrating prototype applications. Figure 1 illustrates such a system, showing that it would be used by various participants at various stages of the construction project. A user would take needed project-specific information from the system, carry out his own data processing, and return to the system newly derived information needed by other participants at the present and later stages.

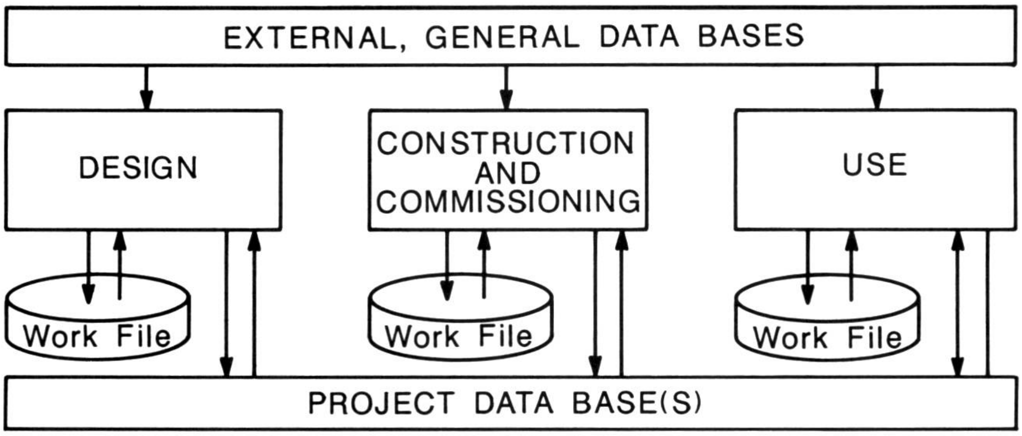

Figure 1. Information flow in the project

The technologies for integrated project information systems may themselves be proprietary. Software packages and the host hardware may be commercial products. The provision of a project information service also can be a private or professional activity. The service can belong to and be operated by the owner if the owner regularly builds and operates facilities; it can be provided by a design organization as a service extending through design and construction and into operation and maintenance; it can be provided by the contractor or by a service bureau specializing in integrated project information system service. However, a number of public, generic technologies are needed to strengthen the service provided by and market for integrated project information systems. These include:

- Information interface protocols allowing automatic exchange of data between the project information system and the diverse data processing systems of the various participants in the project.
- Test methods for the consistency of data so that the data generated by an individual participant and offered to the project information system does not conflict with data already present.
- Techniques to trace relationships between elements of project information, and those responsible for them, so that participants can be warned of proposed or actual changes that will invalidate current data.

2.2 Neutral Data Interface Formats

The neutral data interface format will allow automatic exchange of data between diverse systems of hardware and software with minimal effort in developing translators. The concept is shown in figure 2. Direct translation between two systems requires two translators (A to B and B to A). Moreover, the internal representations of information must be divulged (on A to B and on B to A). For N systems to interact fully, N*(N-1) translators are required and each system must know about each other. For a neutral format, only 2N translators are required and each translator can be proprietary to the system developer. A system developer is responsible for providing a preprocessor to translate from his knowledge representation to the neutral format, and a post processor to translate from the neutral format to the knowledge representation of his system.

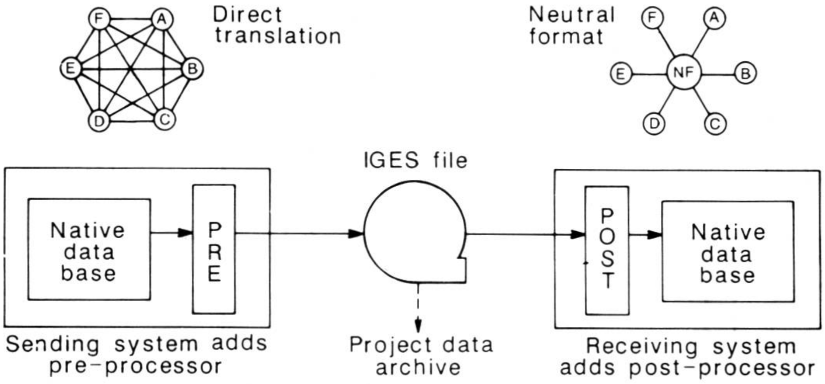

Figure 2. Initial Graphics Exchange Specification

The neutral interface format concept is under development as IGES, the Initial Graphics Exchange Specification of the American National Standards Institute. For Architecture, Engineering and Construction (AEC) there is an AEC/IGES group. NBS provides a co-chairman for AEC/IGES and is conducting research on information protocols for construction and on test methods for assessing the effectiveness of IGES translators [7].

2.3 Machine Representations of Standards and Expert Systems

Standards are a traditional engineering method for representing scientific knowledge and expert judgement as an aid in decision making. A machine representation (computer model) of a standard with user-friendly interfaces and a capability to display the rationale for why the standard is or is not satisfied in a specific instance, is functionally the same as an expert system. Moreover, if it is a machine representation of a consensus standard it has more authority in its judgements than emulations of individual experts and considerably more depth in its knowledge base than the usual rule based expert system.

Standards and codes should become available as machine representations for effectiveness in their use. Indeed, they are partially available as they are incorporated in computer-aided design software by application programs developers. But, there is no assurance to the user that the standard as represented meets the intent of the standard generating organization.

In many years of cooperation with Steven Fenves, the writer and others at NBS have studied methods for developing machine representations of standards. Fenves's work began with the machine representation as a means of data processing in review and design [8]. For a number of years the work explored the machine representation as an aid in standards analysis, synthesis and expression (SASE) [9]. The results are ripe for application in both modes.

A brief example illustrates the potential. Table 1 is a provision excerpted from the national standard for light gage, cold formed steel design. Table 2 represents the information formally as a decision table, and figure 3 represents the conditions and rules as a decision tree. These techniques assist the standards writers to express clearly their intent and to check the completeness and consistency of their provisions. Moreover, it is easy to express the conditions in machine executable form, and the decision tree (that is the flow diagram) can be generated automatically from the decision table.

Compression on Unstiffened Elements

Compression, Fc, in kips per square inch, on flat unstiffened elements:

(a) For $w/t <= 63.3/\sqrt{Fy}$: $Fc = 0.60\ Fy$

(b) For $63.3/\sqrt{Fy} < w/t <= 144/\sqrt{Fy}$⁘:

$Fc = Fy[0.767 - 0.00264(w/t)\sqrt{Fy}]$ Formula (1)

(c) For $144/\sqrt{Fy} <= w/t < 25$:

$Fc = 8000/(w/t)^2$

(d) For $25 < w/t <= 60$#:

For angle struts, $Fc = 8000/(w/t)^2$

For all other sections⁘, $Fc = 19.8 - 0.28\ (w/t)$

In the above formulas, w/t = flat-width ratio as defined in Section 2.2.

⁘ When the yield point of steel is less than 33 ksi, then for w/t ratios between $63.3/\sqrt{Fy}$ and 25:

$$Fc = 0.60\ Fy - \frac{[w/t - 63.3/\sqrt{Fy}][0.60Fy - 12.8]}{25[1 - 2.53/\sqrt{Fy}]} \quad \text{Formula (2)}$$

Unstiffened compression elements having ratios of w/t exceeding approximately 30 may show noticeable distortion of the free edges under allowable compressive stress without detriment to the ability of the member to support load. For ratios of w/t exceeding approximately 60 distortion of the flanges is likely to be so pronounced as to render the selection structurally undesirable unless load and stress are limited to such a degree as to render such use uneconomical

Table 1. Text of Example Provision

			1	2	3	4	5	6
Condition Stub			Condition Entry					
1	$w/t<=63.3/\sqrt{Fy}$	⁘	T	F	–	–	–	F
2	$w/t<=144/\sqrt{Fy}$	⁘	+	T	F	·	·	·
3	$w/t<=25$	⁘	+	+	T	F	F	T
4	$w/t<=60$	⁘	+	+	+	T	T	+
5	Member type = Angle	⁘	·	·	·	T	F	·
6	$Fy<=33$	⁘	·	F	F	·	·	T
Action Stub			Action Entry					
1	$Fc=0.6\ Fy$	⁘	X					
2	Fc= Formula (1)	⁘		X				
3	$Fc = 8000/(w/t)^2$	⁘			X	X		
4	$Fc = 19.8 - 0.28(w/t)$	⁘					X	
5	Fc = Formula (2)	⁘						X

Table 2. Decision Table for Example Provision

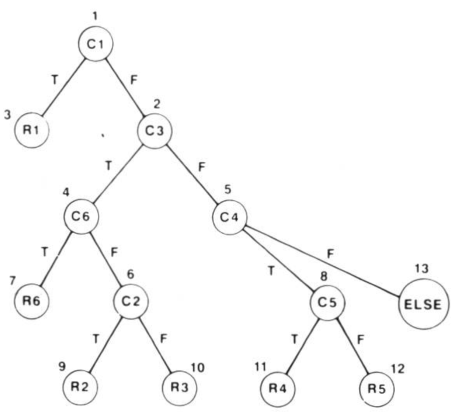

Figure 3. Decision Tree

A complete standard can be represented as a network of decision tables. This is deep knowledge. The representation of the steel design standard is over twenty levels deep and that of the new recommended seismic provisions over fifty levels deep. No wonder that designers are cautious in dealing with an unfamiliar standard or code.

2.4 Interfacing Standards with Application Programs

Computer aided design programs to date have hard-coded the standards intended to be applied. This is a multiply unsatisfactory approach:

- The user has no assurance that the programmers have correctly inferred and represented the intent of the standards writers.
- The application program cannot be used effectively for applications subject to standards other than those coded with the application program.
- The application program is rendered obsolete by an update in any standard it contains. This is costly to the organization that maintains the application program and may become an impediment to the timely improvement of standards.

In cooperation with Leonard Lopez, NBS has been studying the development of a standards interface for computer aided design (SICAD) [10]. The concept is represented in figure 4. Given an agreed upon interface protocol, the machine representation of the standard can be provided by the standards development organization, and the application program can be a proprietary product. The application program can be used anywhere in the world with appropriate machine representations of the applicable standards.

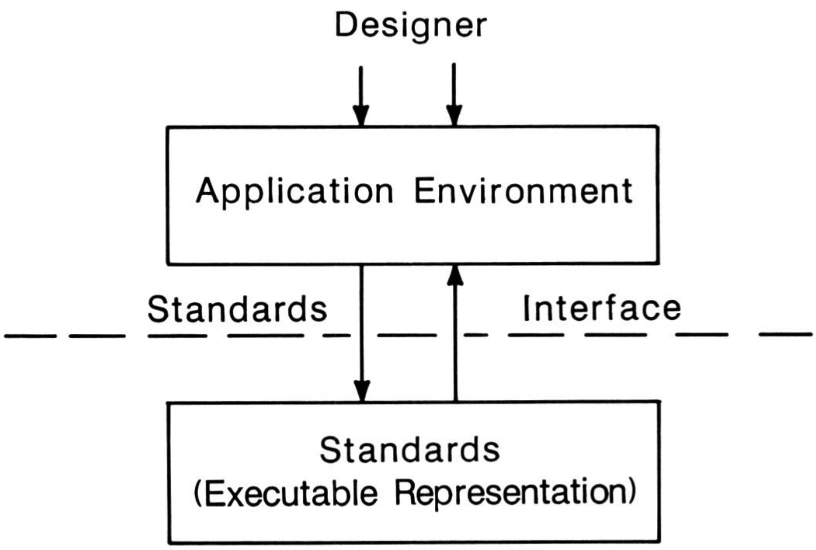

Figure 4. The Standards Interface for Computer Aided Design (SICAD)

3. AUTOMATION ON THE CONSTRUCTION SITE

3.1 Requirements for Construction Automation

A recent workshop [11] combined the insights of practitioners, researchers, and pioneers in factory automation to investigate prospects for automation at the construction site and research needs. Demands for improved productivity and quality will stimulate automation, but severe barriers exist:

- Most projects are unique. Construction approaches the challenge for flexible manufacturing of a product run of one.
- The construction environment is difficult. Loads are heavy, footing is muddy, temperature ranges, wind, rain, snow, etc., must be dealt with. Reliability is difficult to achieve.
- The construction environment is dynamic. Each construction activity changes the environment for itself and others. This is unlike the essentially static environment of a robot in a factory. Safety for men and machines is especially challenging.
- Limitations on capital investment and needs for positive cash flow require that a diverse and dynamic mix of automated and manual activities must be accommodated with a diverse and dynamic mix of hardware and software for the automated elements.

3.2 Metrology

Automation requires that the condition of the site and equipment on it be known in real time. Aspects include: what is there, where is it, and what state is it in? A static world model will not suffice with multiple robots on a construction site. Moreover, this is a promising research area since the practical results will be valuable even without a single robot on the site. Consider the value of real time, as-built information.

3.3 Hierarchical Control

Hierarchical control is a key technology for factory automation [12] and is directly adaptable to construction. In principle, the hierarchy extends back into design stages. Levels range from the lowest, involving movements of actuators, to high levels such as planning of work at a site. Standardization of control hierarchy [13] allows manufacturers of individual devices to create equipment that can be used with other equipment without having to be concerned with anticipating specific circumstances of use.

Construction research can be concerned with improvements of the characterization of the control hierarchy and its information interfaces, and with the improvement of principles of control (sensors, performance modeling, logic and actuators) within a specific level.

Manufacturing Engineering at NBS is exploring deterministic metrology as a successor to statistical quality control. If the tool and the product are sufficiently well characterized in real time, the process can be controlled to prevent manufacture of a defective part. This approach can be fruitful in construction. Chipping out bad concrete is an expensive approach to quality assurance.

3.4 Emulators

How does a potential buyer verify the performance characteristics of a complex item of automated equipment? How does a construction planner test in advance the interactive performance of a variety of automated and manual activities at a site? These tests involve logical as well as physical characteristics. In fields as diverse as electronics, manufacturing engineering, and building technology [13], the emulator concept is being developed in response to these needs. The emulator may play the parts of the environment in which the device operates and the physical behavior of the device itself to test the control logic.

4. AUTOMATED FACILITIES

4.1 Requirements for Automated Facilities

Automated facilities, for example buildings, should be reliable and fail-safe in the inevitable event of malfunctions of operating and control systems. Facilities typically have long life times; automation should allow an arbitrary mix of manual and automated functions and evolution in time with changing operational requirements and improvements in technologies.

Recent experiences at NBS with automated energy management and control systems for buildings have shown the importance of improved performance modeling, information interface protocols, standards and calibrations for sensors, and emulators to test contol hardware and software. These are likely to be applicable to other systems of buildings and to integrated control as well as to other types of constructed facilities.

4.2 Performance Modeling

Much performance modeling has dealt with a passive system responding to its environment. Steady state, static models came first; dynamic models have developed subsequently. For automated facilities design and operation, the control system as well as the physical system must be simulated [14].

Simulation models can be part of the control system to improve control effectiveness. Adaptive control can follow, as the model parameters can be evaluated from real performance of the system. Changes of parameters with time can guide maintenance and warn of unsafe conditions.

Laboratory and field validated reference algorithms for performance modeling allow non-proprietary development of testing procedures without violating proprietary safeguards on specific features of hardware and software.

4.3 Information Interfaces and Test Methods

Well characterized information interfaces are needed for open systems of sensors, software and actuators for facilities automatation. These interfaces define the information for test methods of components such as sensors. The emulator concept has proven fruitful for testing the software of energy management and control systems.

5. SUMMARY

Productivity and international competitiveness in construction require the production of high quality facilities (reliable and fail-safe) in a cost effective way.

Computer integrated construction technologies can contribute to these qualities by supporting open systems of automation in design, construction and operation of constructed facilities.

Key technologies for computer integrated construction include:

- verified, powerful performance modeling techniques
- neutral information interface protocols
- hierarchical control technologies
- test and evaluation methods for hardware and software including quality assurance in construction, diagnostics of existing facilities, and testing software for design, construction or operations control.

Computer integrated construction will require rethinking criteria and procedures for design, construction and operation. Much better formal knowledge of the effects of current decisions on downstream performance is needed to guide decision makers.

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