HIGH PAYOFF AREAS FOR AUTOMATION APPLICATIONS

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ABSTRACT

Construction, although the world's largest industry, is also its most archaic. Most construction practices are very labor-intensive, with resulting impacts on safety, productivity, and quality. The need for automation is apparent. Automation development, however, is expensive and the selection of initial activities for attention need prioritization. A method for prioritization of research efforts is presented. The method is based upon critieria of high payoff areas, receptiveness to automation, and availability of technology. The criteria can be applied to a wide variety of specific activities and areas on different types of projects in particular societies.

INTRODUCTION

This conference is significant in two aspects. First, as the fifth in a series, it illustrates the growing interest and awareness of the need and potential for more sophistication in our construction activities. Second, its location in Tokyo is most appropriate and recognizes the leadership role that Japanese researchers and companies have undertaken.

This paper focuses on construction automation rather than robotics, as a semantic recognition that the word "robotics" implies devices that operate independent of human control after completion of programming. Although robots undoubtedly will have many applications in the construction process, it is likely that many other activities can be significantly improved through partial robotization. Indeed, if the relationship of human conditions and mechanical contributions is expressed by the line shown in Figure 1, it is likely that most construction activities would be located near the left extreme, as much of our current work is quite labor-intensive. Although some progress has been made in the development of small hand tools and cranes for movement of materials, most construction work is heavily dependent upon the availability and skill of construction workers.

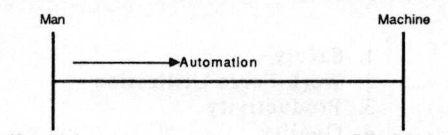

FIGURE 1:
Man-Machine Balance

A partial exception to the above statement lies in those projects that are heavy equipment oriented such as earthen dams, highways, and tunnels. Major advancements have been made in development of larger and more sophisticated equipment for such projects with resulting benefits to society. Of course, even in those areas additional advancements are needed and the projects dominated by such equipment represent a relatively small portion of the total construction volume.

The majority of construction projects are very labor-intensive. In the United States, labor costs typically represent at least one-fourth of total project costs. The impact of labor, however, is much greater than 25 percent since the craftsman's performance influences safety, schedule, quality, and all other associated costs. Indeed, most construction projects are classified as human-driven in contrast to most manufacturing operations that are machine-paced.

It is not likely that all construction activities can be fully roboticized, at least in the near future. Each project is composed of many unique features. Few construction operations are totally repetitious because of changes in geometry and project variations. Thus, it is likely that a variety of automation applications with limited scope will exist. Whereas some construction activities will lend themselves to significant automation improvement, improvement potential for other activities may be more limited.

NEED FOR AUTOMATION

Although construction is arguably the world's largest industry, it is also probably the most archaic. Except for the advancements in heavy construction equipment and minor improvements in hand tools, major changes in construction techniques have been rare. Neither safety statistics nor productivity statistics show progress for the construction industry in the past several years.[1,7] Advancements have been realized in some management practices and information systems, due largely to applications of the digital computer. By all measurable standards, projects have shown little overall improvement in recent years. In 1977, The Business Roundtable (comprised of the 200 largest companies in the United States) embarked upon the multi-year, multi-million dollar Construction Industry Cost-Effectiveness Project (CICE).[9] Recognizing that the construction industry creates society's productive capacity and is basic to the success of its economy, the CICE project identified 223 recommendations for industry improvement. Among those were numerous recommendations implying the need for automation.

Recognition of the need for construction technology research is overdue. The need has evolved as the character of the industry has changed. Historically the construction industry was labor-intensive. Labor was cheap, plentiful, and flexible. Tools, equipment, and material were expensive. Equipment had limited capability. Human flexibility was needed for virtually every task. Structures were simple and required few crafts. High quality of work was often not required. Production could be increased by adding more craftsmen.

Now, however, the situation has changed. Labor is increasingly expensive, particularly where overtime is required. Moreover, demographic studies project a decline in skilled worker availability in many areas. Equipment capacity and flexibility is under-utilized. The need for quality is much greater in some areas. Above all, construction accidents occur all too frequently and the severity of the accidents is intolerable. Projects are far more complex. Automation development is needed to change the nature of the industry to reflect the current situation and to adjust the balance of humans and machines in the construction process.

Obviously the need for construction automation varies among locations and types of projects. The following justifications, however, are offered in priority as generic reasons for automation development:

1. Safety
2. Work Force Utilization
3. Productivity
4. Quality

The potential safety improvements noted above offer adequate justification for construction robotics and automation development. In purely economic terms, the direct and indirect costs of construction accidents have been estimated at 6.5 percent of total project costs.[1] In particular, many accidents involving loss of life could be prevented if machines could be substituted for humans in unsafe environments such as elevated locations or open trenches. The safety reason for automation is, of course, universally applicable and not limited to those societies with high labor costs.

U. S. demographic studies show a gradual, but consistent, decline in available construction workers.[2,10] Not only are the numbers of skilled craftsmen declining, but the willingness of construction workers to pursue a nomadic life and to travel from project to project appears to be declining. Thus, it is likely that inadequate supplies of skilled workers will exist in many regions for traditional construction activities in future years. Similar problems apparently exist in other developed nations.

Construction productivity is a function of many factors. Although most construction workers are well motivated and skilled, administrative delays and work restrictions often result in less production than planned. Overtime or additional shifts often are necessary to achieve adequate production or to maintain planned schedules. Both solutions are expensive. Automation would provide an environment of machine-paced construction that would make productivity more stable and predictable.

Construction quality is generally considered quite acceptable, if skilled craftsmen are available and conformance standards are defined. However, quality is often difficult to measure, particularly at the time of installation. Automation could provide both immediate inspection and verification of quality conformance and consistent levels of quality for particular activities.

STAGES OF AUTOMATION DEVELOPMENT

As presented by Hasegawa[5] and basic to the Wascor project, it is not reasonable to assume that construction automation will conform to current construction activities. Indeed, it is logical to assume that utilization of machines will allow combining many activities into those accomplished by one automated device. Probably, automation development will take place in three stages:

a. Automation of current activities
b. Combining of activities
c. Incorporation of new materials and methods

Initially, the simplest and easiest developments will be those of replacing human tasks with machine tasks. Much research is currently under way in that direction and many prototype devices are developing. As knowledge accumulates and understanding of automation potential progresses, it is likely that multiple activities can be combined into different methods and procedures accomplished by single pieces of equipment. As additional knowledge is gained of automation potential, it is likely that radical changes in procedures and materials will evolve, such as using high strength adhesives for construction joints instead of mechanical fasteners.

Inadequate resources are available to simultaneously pursue automation research in all construction activities. Thus, priorities should be established for immediate and future attention. It would seem reasonable that initial efforts be focused on those activities with both a high payoff potential and a potential for rapidly applying state-of-the-art automation technology. Accordingly, two aspects should be considered:

1. High payoff areas of projects
2. High payoff activities within those areas

Each will be discussed below.

AREAS FOR AUTOMATION POTENTIAL

Earlier studies have identified 17 distinct areas of construction projects.[6,8] The areas, however, vary greatly between types of projects. As shown in Table 1, for example, the labor distribution for buildings is much different from that for heavy industrial projects such as refineries and chemical plants. Whereas almost two-thirds of the craftsmen on building projects represent civil activities, an almost equal percentage are in the mechanical and electrical trades for heavy industrial construction.

Similar results are obtained when considering construction cost distributions such as those shown in Table 2. For buildings, the dominant costs occur in the civil areas, while mechanical and electrical areas dominate for heavy industrial work.

A major additional factor is the relative inefficiency of each area. An earlier study[6,8] identified 15 indicators of difficulty and subsequent inefficiency ratings for the 17 areas of a project represented in Table 2. The results are represented in Figures 2-5 in the form of bar graphs. The length of each bar represents the product of the cost percentage and inefficiency rating for each area. Four types of projects are represented: buildings, light industrial, heavy industrial, and power.

TABLE 1:
Labor Distribution by Craft (%)

	Buildings	Heavy Industry
CIVIL	(64)	(31)
Carpenters	16	8
Cement Finishers	7	2
Iron Workers	14	7
Laborers	17	10
Masons	4	1
Painters	4	2
Roofers	2	1
MECHANICAL	(14)	(38)
Boilermakers	1	2
Insulators	1	4
Millwrights	1	4
Pipe fitters	9	22
Riggers	1	2
Welders	1	4
ELECTRICAL	(12)	(23)
Electricians	11	18
Instrumentation	1	5
OTHER	(10)	(8)
Equipment Operators	4	5
Testers	1	2
Others	5	1
TOTAL	100%	100%

TABLE 2:
Construction Cost Distribution

	Buildings	Heavy Industrial
CIVIL	(64)	(24)
Earthwork	5	3
Foundations	3	8
Structure	27	8
Enclosure Skin	15	2
Interior Finishing	12	2
Roofing	2	1
MECHANICAL	(20)	(49)
Piping	3	24
Plumbing	2	2
Vessels	2	7
HVAC	7	2
Mechanical Equipment Installation	5	10
Insulation	1	4
ELECTRICAL	(11)	(21)
Electrical	9	15
Instrumentation	2	6
OTHER	(5)	(6)
Special Equip. Install.	1	3
Coatings and Paintings	2	2
Fireproofing	2	1
TOTAL	100%	100%

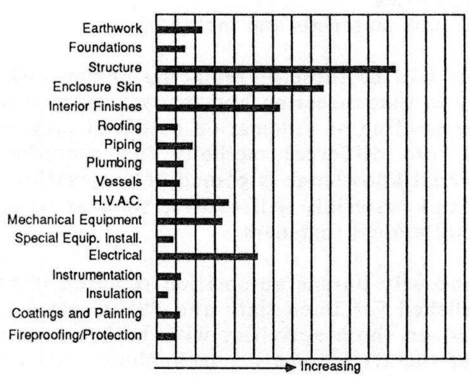

FIGURE 2:
Automation Potential - Buildings

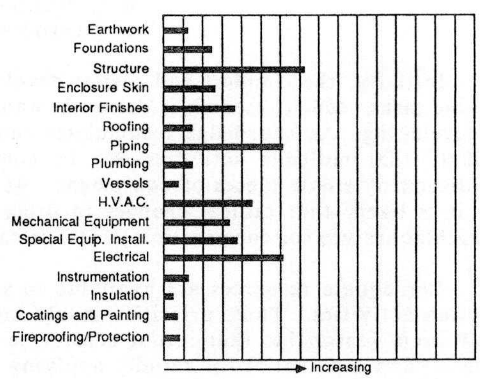

FIGURE 3:
Automation Potential - Light Industrial

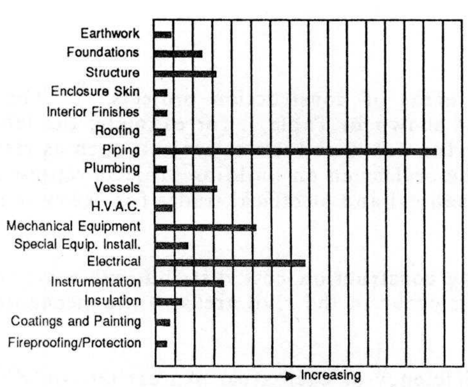

FIGURE 4:
Automation Potential - Heavy Industrial

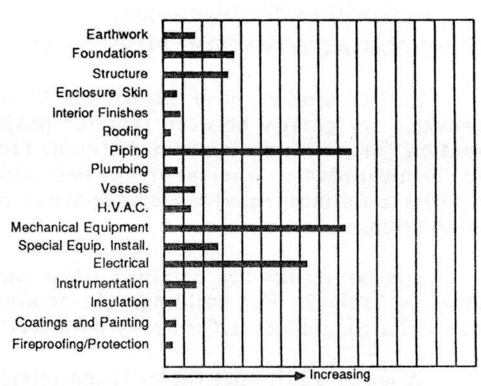

FIGURE 5:
Automation Potential - Power

The illustrations in Figures 2-5 reveal meaningful insight regarding areas of potential economic payoff for construction automation. For example, the highest economic payoff for the buildings sector is that of the structural system, as the single largest cost component, although structural activities are relatively efficient compared to other construction activities. For heavy industrial projects, however, the high payoff areas are those of piping, electrical, and mechanical equipment installation. Piping is not only the largest cost element, but also the most inefficient area of construction activities for heavy industrial projects. Potential areas for power projects, shown in Figure 5, are similar to those for heavy industrial projects, although perhaps less pronounced. Light industrial projects, represented in Figure 3, show characteristics between those for heavy industrial projects and buildings.

The lengths of the bars in Figures 2-5 exhibit clearly the potential for construction automation in terms of economic payoff. Not represented are the characteristics related to safety or other non-economic criteria.

Considering only the labor-intensive types of construction represented by the buildings, light industrial, heavy industrial, and power sectors represented by Figures 2-5, there are nonetheless 68 different areas of construction to be considered for automation development. The particular areas of potential should be considered with respect to relative constuction volume in each particular nation. For example, in industrialized countries, the areas of piping, electrical, and mechanical equipment installation merit attention. For less developed countries, those areas associated with buildings may be more important.

ACTIVITIES

Each area of automation potential consists of several construction activities. Although very little data have been published regarding the relative merits of such activities, an earlier study has provided useful information on a limited number of activities.[6,12,13] Typical data from extensive interviews with construction superintendents and managers are given in Figures 6-8 for the areas of concrete work, piping, and electrical work. Criteria for the plots include complexity, skill required of craftsmen, and dependence on reliable technical information. It is notable that, consistently, those activities requiring the greatest durations are also those ranking highest in terms of complexity, skill required, and dependence upon technical information.

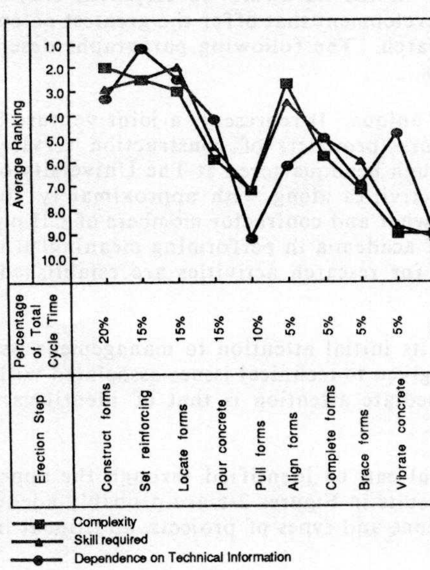

FIGURE 6:
Ranking of Activities in Concrete Work

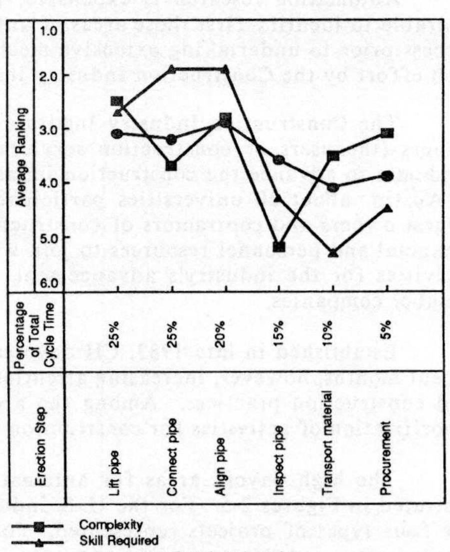

FIGURE 7:
Ranking of Activities in Piping

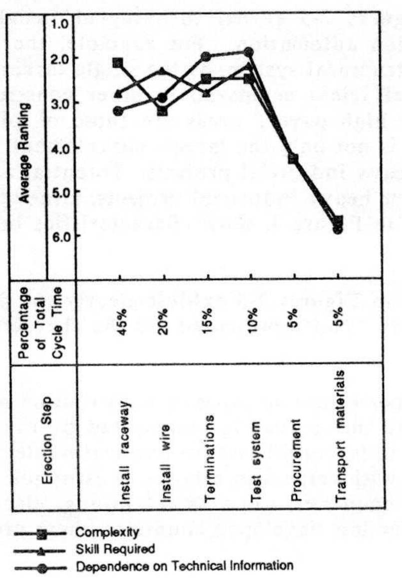

Figure 8:
Ranking of Activities in Electrical Work

The particular activities associated with each construction area vary, in terms of content and in terms of importance. In general, anything involving connections is an activity of concern. The results illustrated in Figures 6-8 are representative only. Much more research is needed to identify adequately the prime activities for automation.

THE CII AUTOMATION PROJECT

Automation research is expensive, particularly in the hardware development stages. It is desirable to identify first those areas of automation development that offer the greatest potential for success prior to undertaking extensive mechanical research. The following paragraphs describe one such effort by the Construction Industry Institute (CII).

The Construction Industry Institute is perhaps unique. It represents a joint venture between owners (the users of construction services), contractors (providers of construction services), and academia to advance the construction industry. Although headquartered at The University of Texas at Austin, about 30 universities participate in CII activities along with approximately 70 of the largest owners and contractors of construction. The owner and contractor members of CII pool their financial and personnel resources to join with those of academia in performing meaningful research activities for the industry's advancement. Priorities for research activities are established by the member companies.

Established in late 1983, CII devoted much of its initial attention to management issues. In recent months, however, increasing attention has been given to technical issues associated with design and construction practices. Among the areas of immediate attention is that of identification and prioritization of activities for construction automation.

The high payoff areas for automation potential can be identified through the approach illustrated in Figures 2-5. For the U. S. industry, the results in Figures 2-5 are probably adequate for the four types of projects represented. For other regions and types of projects, additional information may be needed.

The basic approach for evaluation of automation potential for each high payoff area is illustrated in a matrix format in Figure 9. Six principal functions of the construction process are considered: moving materials, configuring materials, positioning materials, joining materials, coating materials, and quality inspection. The six functions all potentially apply to each of the 17 areas of a project represented in Figures 2-5. Thus for a given type of project such as buildings, a total of 102 functions are possible for consideration.

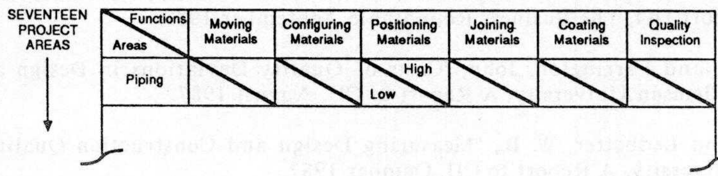

FIGURE 9:
Potential for Automation Payoff

Each function is evaluated according to two basic criteria: receptiveness to automation and availability of technology. Thus for the matrix represented in Figure 9, each box can be divided into two triangles as is shown for "Piping - Positioning Materials." The upper triangle represents an evaluation of that function's "receptiveness to automation," whereas the lower triangle represents the "availability of technology" for that function or activity. General ratings of high, medium, or low are probably adequate at this time for identification of high payoff areas.

"Receptiveness to Automation" can be based on rather specific criteria such as safety, work force needs, productivity, and quality. Quantitative information can be utilized for evaluation in many instances, either by reviewing project records or by taking job-site data through visual observations, time-lapse photography, and other methods.

"Availability of Technology" is a direct function of state-of-the-art technology. Its evalution is necessarily cost-related and dependent, to a great extent, upon the automation needs for the function. For example, appropriate technology needs for some functions may involve sensors only, whereas those for others may involve sophisticated control systems.

The CII project is in its early stages. Many details and procedures will become more clear as the project proceeds.

CONCLUSION

We now live in an exciting era with regard to construction automation. The recent advancements in robotics, computers, control systems, and sensor technology provide adequate technology for immediate applications. Communications and transportation advances allow the research community to readily obtain and share job-site information and thus provide evaluations of automation applications.

Unfortunately, development of hardware for automation is expensive. Funding is expected to be limited and equipment manufacturers are not likely to invest significant funds until the market is more established.

The procedures described above offer an approach for identification of those areas, activities and functions where a high payoff potential is likely. Through such identification, it is possible to utilize the limited R&D resources in an efficient manner and, hopefully, realize significant early benefits from automation research.

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