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Robot Implementation Decisions in the Australian Construction Industry

Cecily Neil, Gustav Salomonsson and Miroslaw Skibniewski

CSIRO Division of Building, Construction and Engineering
P.O. Box 56, Highett, Victoria 3195, Australia.

Abstract

This paper presents a model for managers to use to assess the feasibility of robotising particular tasks on a construction site. A case study illustrates the application of the model with respect to the use of concreting robots on a construction project. This case study highlights the importance of taking into account the overall work process on a site when considering the use of robots.

1. INTRODUCTION

This paper presents a model for appraising the feasibility of robotising particular tasks on specific construction projects. The model was developed from a series of case studies, the results of one of which are presented here. The robots chosen for the prior-use evaluation in the latter study were concrete screeding and finishing robots.

2. PRIOR-USE EVALUATION OF THE AUTOMATED EQUIPMENT

From the work of Blackler and Brown[1], it is possible to define three essential components in prior-use evaluation of new automated construction technologies:

- the direct costs or benefits affecting the immediate project application, as defined by evaluation of both cost-substitution and value-added benefits;
- the evaluation of the wider effects of the new technology on the organisation adopting it; and
- the evaluation of what is likely to be required to ensure a smooth implementation process within the company.

2.1. Direct cost/benefits

Calculating the cost-substitution component of the evaluation of a new piece of automated equipment will involve comparison of the relative costs of:

- the labour, using the two types of equipment;
- the capital involved in the purchase or leasing of the two types of equipment;
- the operating costs for the two types of equipment;
- material waste that can be attributed to the use of the two forms of equipment; and
- any rework that may be influenced by the use of either form of equipment.

Comparison of the relative labour costs will depend firstly on the ratio of the number of person hours required to carry out the task by conventional methods, to the number of person hours required to carry out the task using the new equipment. However, for most tasks, the use of automated equipment would not exclude all manual work: finishing around columns and in corners with concrete screeding robots, for example, would require some manual input. Thus, the design characteristics of a particular project will be significant in determining the savings to be gained from reduced labour requirements. Labour use logistics will also be particularly important in determining relative costs: any savings will be contingent on effective use of all labour required on the site for the initial preparatory or finishing-off work associated with the tasks to be undertaken by the new equipment.

If less labour is required when using a new technology, other benefits may also arise, such as savings from reduced site infrastructure requirements or from a reduced number of stoppages affecting the overall construction schedule – especially if the completion of tasks to be undertaken using the new technology is critical to the production schedule, or if there is a shortage of labour with the appropriate skills. Similarly, the use of robots on sites with a restricted local labour market can reduce the cost of recruiting, transporting and housing labour.

At the same time, however, any additional costs involved in acquiring labour with the necessary skills to operate the new technology will also need to be taken into account in calculating cost-substitution savings. This may be particularly relevant in those companies which are encouraging multiskilling, and pay workmen at the highest rate for which they have trained, regardless of the rate for the particular task they might be undertaking.

The value-added component of the evaluation will depend on:

- the relative match between quality desired and quality that can be achieved using the two forms of equipment; and
- any changes that may occur in customer service (eg improved schedules, better predicability of productivity and completion dates) as a result of using the new technology.

2.2. The effects on the organisation of the new technology

In addition to potential cost-substitution and value-added benefits, the introduction of a new technology may have a number of other organisational impacts, although, for the most part, these will be consequences which cannot be directly quantified. They may include:

- an impact on the health and safety of workers;
- the potential for upgrading an organisation's technological image, which may translate into an improved relationship with construction owners and increasing competitiveness;
- the potential for business expansion into new areas and ventures;
- the impact of any necessary job redesign on the job satisfaction of end-users; and
- any potential impact on the balance of power among different groups in a company.

2.3. Organisational factors influencing the implementation process

Whatever advantages might potentially accrue from using a new technology, the effective realisation of these advantages is likely to be contingent on its smooth introduction.

Labour organisation will be particularly important in this respect. Where labour is organised on a craft basis, if there is any uncertainty over which union's members should use the new equipment, the costs of preliminary negotiations with multiple unions would need to be considered in any evaluation. Australian construction labour is represented by craft unions, which, in the past, have exercised rigid work demarcation. However, recent movements have been made towards multiskilling. It is now proposed that all structural work, for example, will ultimately be carried out by the same workers, with no formal demarcation. If successfully implemented, multiskilling could resolve most of the potential demarcation problems likely to be associated with the use of robots. It would also assist the effective use of labour that might be released from the task that has been automated. Multiskilling may also ensure that training in the use of a piece of automated machinery is not confined to one section of the workforce.

Different styles of management can also be ordered in terms of how effectively they lend themselves to the initial phases of introducing new technologies. The consultative style, for example, is likely to result in the least problems in actual implementation.

A number of other organisational factors are also likely to influence the chances of a smooth implementation process. The policy of using innovative techniques wherever appropriate is likely to facilitate the introduction of a new technology, especially if a company already has an effective procedure in operation for evaluating new technologies. Companies with existing on-site training programs will have a clear advantage if these training programs can be readily modified to incorporate modules relating to the use of the new equipment. Unless its introduction has reached the point where its use is accepted as part of the normal routine, the willingness of employees to use a new technology on-site will also depend at least in part on their willingness and capacity to retrain. Thus, workers' experience of, and response to, using automated equipment, and their computer literacy and attitudes to using computers, will all be relevant. Any language barriers may also present problems either for training or retraining, or for ensuring that guidelines for the safe use of a new technology are fully understood. Finally, the company's equipment acquisition policy, and its cash flow model for the use of equipment, will help determine whether the company can afford to lease or purchase new equipment.

Ultimately, the feasibility of introducing a robot may depend on the extent to which the appropriate characteristics for its smooth introduction already exist in a company, or, if not, whether certain organisational changes are warranted in order to enable this to take place.

3. A CASE STUDY APPLICATION OF THE MODEL

The case study chosen to illustrate the above prior-use evaluation involved examination of the concreting work in a $30 million project consisting of the renovation and addition of five floors to an existing building. The site was located in the central business district of a major city. Although access was limited, this would not have hindered the use of smaller robots.

The contract was based on a fixed price, and the time allowed to tender for the contract was not sufficient to permit a non-conforming bid. Thus, there was no opportunity for the contractor to modify the design to suit any technology he might wish to use. Most tasks on this project, including the concrete work, were subcontracted to specialist subcontractors.

3.1. Basic characteristics of the concreting task

The construction techniques employed on this project were conventional. The structure to be built was reinforced concrete, and involved a total slab area of 22 500m^2. The concrete was placed using the combination of a concrete pump and a crane with bucket. The average work cycle to complete a floor level was 1.5 weeks, with 2 pours per week. The surface finish was obtained using walk-behind power trowels, although the numerous column and bracing wall sections in the layout meant that approximately 25 per cent of the slab area was inaccessible to the power trowels, and had to be finished by hand trowelling. The average size of a pour was 1000 m^2. There were some 23 pours completed by a team of 11-12 men.

3.2. Potential for using robots

A prior-use evaluation was carried out for a concrete levelling and screeding robot and a finishing robot. The machine considered for the levelling and screeding was a vehicle-mounted screeder developed by Takenaka. The machine deemed most applicable for the concrete finishing on this site is one manufactured by Schimizu. Although there are well-established travel path algorithms to cover even the most complex areas[2] that would have enabled programmable robots to have been used even on this particular job, the machine selected is remotely controlled by an operator. On jobs such as this, the concrete slab areas are frequently of varying depths. The uneven exposure to the elements due to the surrounding buildings can cause an uneven initial curing resulting, as it did on this job, in large wet patches located in the areas otherwise ready for trowelling. A remote-controlled machine would have provided an opportunity for the operator to detect any such patches of concrete not properly cured, and respond accordingly.

3.3. Prior-use evaluation from the perspective of the subcontractor

The subcontractor awarded the tender for the structural work was a family firm which, six years prior to this project, had been set up to undertake full structural packages. At the time of the project, the subcontractor had undertaken projects ranging in value upwards to $18 million for many of the local leading firms in the construction industry. Five separate projects were being carried out by the subcontractor at the same time as this contract, although the amount of work on hand at any point of time was variable. The largest contracts undertaken had involved 50 to 60 of the subcontractor's employees; the smallest, around 7 to 8.

The subcontractor maintained a permanent workforce, numbering around 140 to 160. The average length of service of the subcontractor's employees was around three to six years.

3.3.1. Direct cost/benefits: cost-substitution savings

Overall labour requirements: The concrete pour was usually commenced early in the morning. Levelling, screeding and finishing started after a suitable time lag, and ultimately involved the whole team that had initially worked on the pour. Work would usually finish in the late evening. While not all men necessarily worked an equal number of hours on any one pour, each team member was paid according to the total number of hours the pour took. Hourly cost for concrete labour was approximately $30, including all overheads.

The use of a concrete screeding robot on this project would have required an operator plus one person to assist. Concrete finishing robots require at least one skilled worker to operate the machine, set up and dismantle the robot on a site, and ensure that proper transport procedures are strictly followed. The cost of operator labour may be somewhat higher than that of a traditional concrete labourer, given the specialised training required, but should not exceed $45 per hour. However, it would be necessary to train more that one person in a team to operate each robot. Given the subcontractor's policy of paying his men at the rate appropriate for the highest level of skill they have attained, this could to some extent inflate the general labour costs among those not operating a robot at any given time.

It was estimated that due to the complex floor layout, approximately 25 per cent of the work would still need to be done manually, and that two people would be required for this work.

Labour logistics: The use of concrete screeding and finishing robots would lead to some reduction in labour costs through enabling the entire team to complete the concrete finishing in fewer hours than required using conventional methods. However, any additional labour cost savings would depend on efficient labour utilisation. The logistics of efficient labour usage in conjunction with the use of the robots for screeding and finishing seemed to present the greatest barrier to labour cost savings through the use of the concrete robots on this site. Using screeding and finishing robots would reduce the number of men required after the concrete placement had been carried out. However, given the way the work was organised with respect to the concreting team, labour cost benefits could only accrue from using a robot if:

- work could be found for the men responsible for pouring concrete who were surplus after the pour had taken place; or
- the number of people required for the initial concrete placement work could be reduced.

The subcontractor felt that it might have been possible to reduce his team size on this project by 2, and still place the concrete efficiently. However, factors such as concrete truck delivery delays and intermittent site inaccessibility due to traffic jams would have made making any substantial reduction in team size particularly difficult.

The alternative of finding work elsewhere for surplus team members would have proved much more difficult. It would have necessitated:

- the use of a multiskilled work force, which could be used on alternative skilled work;
- the use of unskilled labour on the concrete pour, with the possibility of using this labour for unskilled tasks when the pour was finished; or
- the company having a sufficiently large portfolio of projects with pours on the same day, so that a crew could finish pouring on one site, and then move to another for a second pour.

Given that the subcontractor was contracted to undertake all the structural work on this project, the first of these two options appears to have been a viable long-term option, although labour was not yet sufficiently multiskilled for this to have occurred on this project. The second option was also theoretically viable, but the deskilling of the work and breaking up of the team organisation would have been unpopular. The logistics of the third option made it unviable. Thus, on this particular site, productivity savings could not have been fully realised, and potential labour cost savings were, therefore, substantially reduced.

Equipment cost: The type of equipment costs to be compared included those associated with the robots on one hand, and those of manual screeders and engine-powered helicopters on the other. The purchase cost of the types of robot discussed here, when commercially available, was estimated to be likely to be around $50 000. This figure would have been financially viable for the subcontractor, and would not have had to be offset against a single project in order to avoid cash flow problems. The cost of owning and operating each of these machines was estimated to be likely to be around $400 per day, but will vary with the supply and demand.

The cost of the dumping levellers, straight-edge boards and vibrators is very low, and was therefore not included in this comparison. The purchase price for the most commonly used helicopter trowels is around $1500, rising to $2500-3000. These types of machines usually remain operational for many years with a minimum of maintenance, and are very economical to run. Discussions with concrete contractors and hire companies indicate that an average cost of owning this equipment, including fuel, would not exceed $50/day.

Rework: On some sites, the use of concrete screeding and finishing robots may reduce the total amount of rework necessary, thus reducing cost and minimising schedule delays. However, most of the concrete rework that had to be done on this site was patching necessary as a result of rain that had occurred after pours had taken place. According to the subcontractor, none of the rework that had been necessary could have been avoided by the use of robots.

Material waste: Material waste in the concrete work on this project had been around 0.2%, and again, would have been unlikely to have been reduced by the use of robots.

Table 1
Summary of comparative assessment

Cost category	Traditional work ($)	Cost category	Robot assisted ($)
Concrete Pump (8 hour)	1 920	Concrete Pump (8 hours)	1 920
Crane (1 day)	400	Crane (1 day)	400
Crane Crew (9 hours)	1 260	Crane Crew (9 hours)	1 260
Traditional labour (12 men/11 hours/$30)	3 960	Traditional labour (8 men/9 hours/$30)	2 160
		Robot operators (2 men/9 hours/$45)	810
		Screeding robot (1 day level & screed 750 m²)	400
Helicopter Trowels (2)	100	Trowelling robot (1 day trowel 750 m²)	400
Total Traditional	7 640	Total Robots	7 350
Traditional/unit slab	7.64/m²	Robotic/unit slab	7.35/m²
Job total - traditional (22500 m²)	171 900	Job total - robotic (22500 m²)	165 375
Difference			- 6525

Summary cost-substitution savings: Overall, cost-substitution evaluation suggests that the total direct substitution benefit in this case would have been around $6525 (Table 1). The savings in these initial calculations are those likely to be accrued after the employees have reached the top of the learning curve for the use of the particular robot. Since this is not likely to be achieved the first few times the machines are used, the calculations to some extent overstate the labour savings likely to have accrued on this particular project.

3.3.2. Direct cost/benefits: value-added benefits

Schedule savings: Since concrete placement operations are usually on the critical path in construction, shorter performance times may translate into a cash bonus if it means project delivery ahead of schedule. However, the size of the pours possible on this site was a major determining factor in the scheduling of concrete finishing, and it was unlikely that even if finishing times could be reduced, it would have been possible to increase the frequency of pours. In some situations, the shortened performance time for finishing might also help in project resource allocation should shortages of skilled labour take place in the course of the project. However, this was not a problem on this site.

Stoppages and delays: The subcontractor felt that this particular project had been one of the fastest jobs he had undertaken for the design type. There had been no industrial stoppages affecting the concrete work, and the only serious delays that had occurred had resulted from the weather. Thus, the availability of the robots would not have substantially reduced time lost.

Improved work quality: Robotic concrete finishing may sometimes translate into a better quality concrete surface by avoiding the human error inherent in the traditional performance of these tasks. According to both the contractor and the subcontractor, however, there had been no problems achieving the desired quality of concrete finish on this project.

3.3.3. Organisational effects of introducing robots into the company

Improved health and safety of workers: There were no major accidents on this site. However, concrete levelling and screeding are physically demanding tasks, often requiring brute force to disperse large volumes of concrete mix on the floor surface. Cements used in concrete mixtures may contain varying doses and types of fly ash, some of which are slightly radioactive. In addition, cases of human bone and ligament disorders caused by handling work tools subject to low frequency vibrations have been reported; concrete mix vibrators may, therefore, create a potential health hazard to the workers using them. Hearing and back problems are also prevalent among concreters. The robotic performance of concrete tasks may, therefore, lead to a long-term reduction in various health problems and hearing problems.

Impact on labour supply: By reducing the number of men necessary to do the concreting, the use of robots can reduce any problems that might exist with respect to the supply of skilled labour. According to a director of the subcontracting firm, there has been a problem in the supply of skilled concreters over the last couple of years, reflected in the fact that concreters are among the oldest of the company's employees. He foresaw an increasing problem in recruiting sufficient skilled concreters in the next ten years - although it has been suggested that this may change with the growth of multiskilling. The introduction of screeding and finishing robots could, however, help to forestall any possible impending shortage of skilled labour.

Potential for business expansion: Potential for business expansion as a result of a company's introduction of robots onto this construction site could come from several sources, including:

- a greater capacity to win contracts as a result of an improved technological image; and
- the acquisition of new workforce skills that could either improve competitiveness, or make it possible to tender for work not previously undertaken;

Since the subcontractor was already winning tenders with a number of major contractors, the chances were that any experience gained through the use of sophisticated automated equipment on one project could readily be turned to an advantage on other projects. However, the firm already used some of the most up-to-date equipment available, and the general consensus in the industry was that while technological sophistication might impress a client, in the current economic climate it was not a factor likely to be particularly significant in the winning of tenders: the only factors the owners consider important are tender price and the contractor's reputation as a solvent business with a record reflecting an ability to deliver the required services. Further, in the current economic climate, the scope for moving into new areas of construction are limited. Nonetheless, the company's acquisition of skills relating to the use of robots, if appropriately integrated into the work organisation, could significantly improve overall productivity, and thereby be a worthwhile asset with respect to obtaining subsequent contracts. The subcontractor's labour retention policy ensured that skills acquired by his employers would be retained in the company.

Impact of any necessary job redesign on the job satisfaction of end-users: Since the robot operators would still be very much part of the team work, they were unlikely to become isolated in the work context, as can happen with the use of robots in mining, for example. However, the subcontractor's use of robots on this site would have influenced the job design of concreters who became robot operators for this project in several ways:

- the work would have been less strenuous and dirty;
- the impact of most robot operators' personal skills on any one project would have not been so much on the quality of the finished product, but on their skill in keeping the job on schedule through efficient programming and set-up and dismantling;
- there could have been a potential reduction of individual initiative and decision-making, depending on whether the robot operator was employed predominantly as a machine minder, or trained to program and do minor maintenance work;
- the training to use robots would almost certainly have resulted in pay increases; and
- the introduction of robots could have introduced the opportunities for personal advancement, and continued work opportunities for older workers or workers who had sustained previous injuries that restricted their ability to undertake strenuous work activities.

The actual changes to the job design that would have come about for concreters working on this and future projects utilising robots, had concrete screeding and finishing robots been introduced, would have depended on the way in which work arrangements were reorganised, the number of men trained as robot operators, and the frequency with which trained operators were likely subsequently to be using robots, rather than carrying out other structural work. These factors, together with the current sources of job satisfaction and work values of operators, would have, in turn, influenced the impact of using robots on job satisfaction.

The decisions regarding the reorganisation of concreters' jobs would have needed to have been carefully made if this company were to have used robots. In particular, the potential disadvantages of training only a few men would have had to be weighed against the costs of upgrading the skills of the majority of the workforce, both in terms of training and subsequent rates of pay. In making these decisions, it would have been necessary to have had, *inter alia*, a clear understanding of sources of job satisfaction among the men involved in using the machines, in order to achieve a job redesign that would minimise any detrimental changes in those areas important to their job satisfaction.

Interviews with the concreters working on this job suggested that ensuring that robot operators remained part of the work team would have been important as well as feasible. The concreters usually worked in teams made up of approximately the same group of people. All regarded working with people whom they found friendly and easy to work with very important. The *status quo* appeared to reflect preferences with respect to team structure. Thus, if robots had been introduced, it would have been important that the majority of men did not find themselves regularly working on their own.

The importance that all the concreters interviewed attached to being able to make good use of their skills could have also presented some problem if only a few people were trained to work continuously as robot operators. However, in other respects, the interviews suggested that the possible changes to work patterns that could have come about as a result of job changes induced by the use of robots would have been unlikely to have had any serious impact on job satisfaction for the majority of concreters. Only a minority of those interviewed, for example, regarded being able to use initiative or being able to make decisions about how they did the job as very important. Similarly, the scope for increased personal advancement offered little prospect for significantly improved job satisfaction for the majority of the workers interviewed - the latter were equally divided as to whether having prospects of some sort of future career path was very important, important, or unimportant. Nonetheless, given that the workforce is an aging one, the introduction of a technology that reduced the physical effort involved in concrete work could be an important factor in prolonging the ability of employees to continue in concreting work, and in relieving the pressures on younger workers obliged to carry a disproportionate load of the most strenuous work.

Potential impact on the balance of power among different groups within the organisation: While the use of robots might improve productivity, the possibility of doing the work by conventional methods would not be excluded by the introduction of robots into a company. At the same time, if robots were introduced, there would never be a process of total deskilling among concreters, although the traditional skills of the tradesman might be less important to a project than previously. Indeed, the training required for robot operators would involve a process of reskilling rather than deskilling. Thus, the introduction of robots would have been unlikely to have had a significant impact on the pre-existing balance of power between management and workers in the company. In any case, the management-worker relationship in the company was such that this was unlikely to have been a significant issue.

3.3.4. Organisational factors influencing a smooth introduction

Managerial technological knowledge and approach to evaluating new technologies: The equipment the subcontractor used tended to be the most up-to-date in the field for the work being carried out: thus, there was no resistance to change in the company's management structure. There was, however, no formal procedure for evaluating new technologies.

Nature of industrial relations: The director of the subcontracting company prided himself on the quality of the company's industrial relations. The firm sought to be supportive to employees in all matters, and industrial disputation was said to be low.

Company training programs: There were no formal training for concreters in the company. Some changes would have been needed in this respect if robots had been introduced, to train both operators in the use of the machines, and the remainder of the team in safety guidelines.

Language barriers: Permanent employees had a wide range of different nationalities. However, language was not considered to be a problem with respect to team work, passing on instructions or training.

Workers' experience of, and response to, using automated equipment: The closest that any of the concreters interviewed had come to using semi-automated or automated equipment was the use of helicopters for concreting. Only one of the men had ever used a computer, and there were mixed reactions among the remainder with respect to learning to do so.

Equipment acquisition policy and cash flow model for use of equipment: The subcontractor was a well-established firm in a position to be able to afford to either lease or purchase a medium-priced robot. Thus, it would not have been dependent on a possibly reluctant plant hire firm for the supply of concreting robots.

4. CONCLUSION

Analysis suggested that there were no major impediments to the smooth introduction of robots on this site. It also showed that there could be some definite advantages for the organisation in their introduction. However, the estimated cost-substitution savings on this project were only $6525, due primarily to some limited construction labour savings. It is unlikely that any company would be prepared to introduce a new technology for such limited cost savings. However, it is possible that larger substitution benefits could have been achieved on other projects concurrently in the contractor's portfolio, provided that more suitable conditions for the robotic performance of concrete screeding and levelling existed. The capacity to use robots on a number of sites simultaneously would have further increased their attractiveness to the company. Nonetheless, on this project alone, the introduction of concreting robots would have been basically uneconomical.

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