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Prior-use evaluation of the impact on company work procedures of using robots on construction sites

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Abstract

This paper demonstrates the application of a prior-use evaluation model developed to assist management to evaluate the probable impact of introducing automated equipment on construction sites. Two case studies have been used to illustrate the importance of not only considering the particular project characteristics, when assessing the potential benefits associated with automated equipment, but to include the whole range of work procedures practised in the company as a whole.

1. INTRODUCTION

The research reported in this paper was part of an overall effort to develop a prior-use evaluation model designed to assist project managers to evaluate whether construction robots currently in use overseas would be appropriate for use on particular building projects in Australia [1,2]. The model enables managers to make prior-use evaluations of automated construction equipment and is based on the result of a series of case studies[2,3]. Following the work of Blackler and Brown [4], four essential components in prior-use evaluation of new automated equipment have been defined:

- the direct costs and benefits affecting the immediate project application, as defined by the evaluation of both cost-substitution and value-adding benefits;
- the potential subsequent effective utilisation of any new technology introduced;
- the evaluation of the wider effects of using the new technology on the organisation;
- the evaluation of what is likely to be required to ensure a smooth implementation process.

In this paper we will examine two case studies concentrating on the work sequences involved in the installation of formwork and reinforcement, and internal painting.

2. FORMWORK AND REINFORCEMENT

This project involved the turn-key construction of a $200 million new high-rise five-star hotel with 570 rooms. The basic structure is a reinforced concrete frame with a cladding of polished pre-cast concrete panels.

2.1 The structural work

The work methods and construction techniques involved in building the concrete frame on this project was mainly conventional, despite some unusual structural features in the foundation and the below ground section of the building due to a road tunnel underneath the building. Three specialist trade sub-contractors were engaged to construct the concrete frame: a formwork contractor, a contractor specialising in reinforcement and associated steel work, and a concrete contractor. The work schedule for the typical floor was based on a five day work cycle, and there was three pours to a typical floor. The concrete frame structure involved about 150 pours with an average pour size of 400 m^2 ranging from 300 to 500 m^2.

2.2 Work procedure

2.2.1*Formwork*

The formwork contractor used their own prefabricated table formwork for slabs and beams, a crane climbing jump form system was used for the service core, and square and circular steel forms were used for the columns. The forms required for infill and block-out pieces or other special configurations were made up in situ using conventional form plywood panels. No automated formwork system to replace the manually placed beam and slab soffit formwork seems yet to have been developed. There are only the semi-automated systems of the climbing, jumping and sliding forms both of which are already widely used in the construction industry and therefore will not be considered in this examination.
The formwork for a typical floor slab pour was on average completed in 324 person hours over a 1.5 day period, with an average team of 27 people. The overall amount of formwork installed was 125 000 m^2.

2.2.2*Reinforcement*

Reinforcement was mainly assembled on the table formwork platform with the exception of reinforcement-cages for the columns which were pre-assembled at ground level. The material required was lifted by the crane and placed in the work area. The crane also assisted with the final positioning of the column reinforcement-cages and other heavy steel items such as beams and girder trusses. Reinforcement bars were manually carried into position, placed and tied.
The installation of reinforcement and other cast-in items for a typical floor slab pour in the tower was performed with an average labour input of 260 man-hours over a 1.5 day period, and an average team of 20 people. The project involved the placement of 4 500 tonnes of reinforcement bars and mesh.

2.2.3 Work flow

The work flow sequence practised by this builder and his subcontractors had been developed over a period of many years and been proven to work very well for their mutual benefit. Basically, the table formwork sections on any given level was quickly rolled into place, preliminary positioned and secured. In this way a reasonably large working platform for the steel fixing team to begin assembling the reinforcement was provided in a matter of only one or two hours. This enabled work to proceed simultaneously with steel fixing and final formwork detailing on top of the form work and the proper securing and propping underneath. Thus, both formwork and reinforcement could be completed in 1.5 working days, which was critical in achieving a five day work cycle per floor level.

2.3 Potential for using construction robots

Both the installation of formwork and reinforcement are physically strenuous and demanding tasks as well as labour intensive. They are also regarded as high risk trades and the workers are prone to suffer long term injuries and problems to back, shoulders, neck, arms, legs and ligaments. The formwork platforms where the steel fixers have to perform their work are also often slippery, especially in damp or wet weather conditions, and slips, trips and falls are a common occurrence. According to the steel fixing subcontractor, it would not be unusual for 15 to 25 percent of his workers to be off work suffering from work place related injuries at any particular time. The formwork contractor had not kept any detailed statistics on the proportion of his work force that were off work due to work place injuries, but estimated the proportion to be in the order of 5 to 10 per cent of his work force.

The immediate potential benefits of using an automated machine to assist with the reinforcement would be an increased productivity which could result in either the use of less manpower or a shorter completion time. The effect of this is directly measurable by cost-substitution savings and value adding benefits. There could also be other consequences which cannot be directly quantified, such as:

- better job satisfaction among the steel fixers with less strenuous work;
- improved health and safety for the workers; and
- extended working life for older workers or an opportunity for continued work for workers physically restricted by previous injuries.

The machine selected as the most suitable (it was in fact the only one we managed to locate) for assisting with the carrying and placement of reinforcement bars on building constructions was the *Robot for Placements of Reinforcing Bars - MR-38* developed by the Kajima Corporation in Japan [5]. The likely overall impact of introducing the machine on this project was evaluated in close collaboration with the main contractor and the two trade contractors.

2.3.1 Direct cost/benefits

The use of MR-38 would eliminate the need for manual lifting and carrying of reinforcement on the work deck and would, according to the manufacturers claim, normally reduce the labour input requirement by about 50 per cent. However, due to the amount of post tensioning involved in some walls and slabs, the large number of structural steel items and components, and column reinforcement-cages to be pre-assembled, the actual reduction was estimated to 35 per cent. Although, there was some saving in labour costs, this was balanced by the increases caused by the use of the robot and the improved stronger table formwork required to safely carry the reinforcement-bar machine (about 7.5 tonnes) in operation. There was no significant cost difference in the total cost calculated for the two methods. Should the machine have to run on top of already installed reinforcement its use was perceived to cause dislocation of some bars or damage some barchairs, which could result in an increase in rework. According to the steel fixing contractor the amount of material waste normally varies between 2 and 4 per cent and no improvement could be foreseen in this respect by the use of the reinforcement-bar robot. If anything, the use of this heavy machine could quite possibly bring about a slight increase in waste generated.

2.3.2 Value-adding benefits

Due to the work procedure practised by this main contractor, with formwork and reinforcement carried out simultaneously in the same area, no gains in completion time were possible. According to the site engineer the load bearing capacity of the standard type of table formwork used was not sufficient to safely allow a 7.5 tonnes machine to operate on the formwork. The method used for the initial placement of formwork sections could not provide a sufficiently and safely secured area onto which the machine could have been brought, even if the table formwork section were made stronger. The formwork contractor estimated that to provide such an area would have required almost a full day. This would have increased the five day work cycle per level to at least seven days. A result which was unacceptable to the project management considering the risk of incurring a claim for liquidated damages, which was stipulated in the contract at $250 000 per week, in the event of any delay in project completion.

The use of the robot would not have been likely to improve the quality of the completed reinforcement mainly due to the combined effect of the very strict requirement set out in the Australian standard for reinforcement work and the careful inspection carried out by both council inspectors and the site engineering staff.

2.3.3 Organisational effects

It was generally acknowledged by the management teams that the introduction of an automated reinforcement bar placement robot would be likely to provide significant improvements in the health and safety of workers. The direct effects of such a machine would be a substantial decrease in the amount of heavy lifting and carrying which would be likely to result in less work related injuries and illnesses causing lost work time. Another benefit would be the reduction in the number of workers operating at heights and thus being exposed to the risk of suffering critical or fatal falls.

The introduction of a reinforcement robot would improve the job satisfaction among the steel fixers by removing some of the more strenuous tasks. It would also improve the possibilities for older workers to remain active in the trade should they so prefer. In the same way it would enable workers physically restricted through the effects of previous injuries to continue in their trade and thereby retaining their skill and experience in the work force. The possibility to train as a robot operator would open an additional career opportunity and be likely to result in better pay.

2.3.4 Evaluation

After having gone through the assessment procedure step by step the main contractor and the trade contractors generally agreed that the reinforcement-bar robot would not have been used on this particular project. The main reason for this was that the robot could not be brought safely into operation on the table form work due to the inability to provide a sufficiently large and fully secured area of form work without a radical re-engineering of the table form work system and the work procedure. This was not in their opinion a matter that could be resolved in isolation for individual projects, but needed to be considered in the context of the work procedures and management policies of the company as a whole.

3. INTERNAL PAINTING

There are a number of automated spray painting robots that have been developed for site use. The robots that have been fully developed are all designed to spray exterior surfaces of walls and columns or interior surfaces of tall structures, such as silos, where accessibility is very limited or difficult.

There seems to be very few robots designed for interior finishing tasks and none have been developed further than to full-scale feasibility model stage. One interior finishing robot has been developed by the Israel Institute of Technology in Haifa [6]. This robot, "Tamir", is a full-scale multipurpose robot capable of building interior walls and partitions, laying tiles and applying surface finishes by spraying. It will be examined in its spraying capacity to see whether it would offer a worthwhile alternative to the current techniques used on this project. Since, at this stage there exists no site based production rate data, no prior-use evaluation has been possible.

3.1 Project

The project involved the refurbishment and expansion of an existing race track facility, including the construction of two racecourse grandstands, each with five levels including a basement. The work involved glass wall enclosure of spectator stalls, construction of a number of service facilities and the installation of heating, air conditioning, and other amenities. One grandstand had a fully suspended 12 m high glass wall.

The facility has large wall and ceiling surfaces both inside and outside, resulting in a large volume of repetitive painting. With traditional painting methods, the large dimensions of individual walls necessitated the use of demountable scaffold systems and in some instances mobile scissor lifts scaffold. The bulk of the ceilings represented a large area of variable height, requiring frequent changes in scaffold height. The amount of painting work on the ceiling areas represented about 30 man weeks. This made up 40 per cent of the painting contract.

3.2 Work procedure

The painter used a combination of a large mobile scissor lift scaffold and a demountable scaffolding system. The paint finish to most ceiling areas and high wall areas was applied with a spray gun and the productivity using this technique was likely to compare favourably with that of the intended robot. The lower wall areas were painted using conventional paint rollers with extension rods from the floor. Wall areas above say four metres were finished from scaffolding using a spray gun where suitable and with rollers elsewhere. All close detailing such as cutting in around doors, windows and timber details, as well as the timber detailing was done with brushes. The lower wall sections contained a large number of windows and openings fairly closely spaced.

3.3 Potential for using a spray painting robot

The ceiling heights varied in a stepwise fashion from 3.5 metres to some 12 metres and this made the use of a wheel based mobile automated spray painting machine rather impractical. More than 50 per cent of the ceiling area was above the 5 metres level. Although, no detailed information on the actual vertical reach is available on the "Tamir" spray painting robot it is assumed that it would possibly be able to reach ceilings of no more than five metres in height. To enable a larger reach would most likely require a significant redesign of both the base vehicle component and the manipulator arm.

The painters generally argued that the labour logistics problems associated with painting either small confined areas or areas with many and closely spaced windows and doors made the use of the spray gun impractical for two reasons.

Firstly, the coordination of the manual painting work required in association with and supplementary to the spray painting robots work can present a problem. This include tasks such as cutting in around windows, doors, timber details and areas finished in other materials or substances not to be painted. To reduce this work protective covering and masking can be carried out in advance of the spray painting. However, this is often quite arduous and time consuming and could in the painters experience make the spray operation uneconomical.

The extent to which cutting in around windows, doors, timber and other detailing can present a problem would depend partly on the type of paint being used. In cases where flat or low sheen acrylic paint were used the cutting in could safely be carried out the next day. On the other hand where gloss acrylic or oil based enamel paints were used at least one painter would be required to carry out the manual work while the spray robot was operating. This would require the painter doing the manual work to also be wearing a fresh air flow helmet as a protection against the spray fumes. A factor that is not viewed favourably by the painters since they claimed that this is often cumbersome, uncomfortable and severely hamper their productivity since the cutting in operation is a precision task. In their experience the viewing panel in the helmet invariably get scratched and smudged, which makes vision more difficult resulting in fatigue and sore eyes at the end of the day.

Secondly, a critical aspect of being able to perform spray painting is the need to get exclusive and undisturbed access to a clear area (room) for the duration of the spray painting operation. The reason for this is that before spraying can begin the surfaces to be finished must be properly prepared, eg. any indentations and scratches filled, dust, dirt and grease removed and rough patches smoothed. Any protective covering and masking required must also be attended to. Thus, no activities or traffic by other trades can be allowed in the area during this time. The spraying of paint always generates a fine mist which, especially in confined areas, is detrimental to human health and any person present in the area where spraying is in progress must wear a protective fresh air flow helmet.

There was a general consensus among the painters and the main contractors site management that these circumstances were very difficult to achieve and would in many cases be impractical due to the compact scheduling requirement and complex work sequencing. They claimed that to rearrange the work schedules to enable spray painting for the whole job would require the work processes and procedures of several other trades as well to be substantially redesigned. However, two trends were said to make such changes highly unlikely:

- the overall schedule is often running late by the time the painters come on site, so that the latter not only find themselves competing with other trades for access, but have damage inflicted on their work by other trades during or after its completion; and
- contractors tend to bring painters onto a site as early as possible because of the psychological impact that their arrival usually has for other trades; it symbolises the fact that the project is close to completion; and in the opinion of the contractor it encourages an increased sense of urgency.

Another point made most strongly by both the painters and the main contractor was that the conventional method of painting had a distinct advantage over spray painting by a robot. With the conventional method the painters can directly check the surfaces or items for defects and take corrective measures before applying the finish. On this job, where a large proportion of the ceiling areas were too high for normal inspection, the painters had been checking the adequacy of the plaster finish, rectifying minor flaws and had made the necessary surface preparations as they progressed with the job. It is unlikely that the visual sensors on a painting robot would be sufficiently sensitive so as to accurately detect and properly diagnose the type of defect, and let alone instigate an appropriate corrective measure. Especially since a large part of the ceilings were above five metres in height and the spray painting robot would be operating from the floor level. From a quality control perspective this is possibly the most critical factor since no paint finish can be made any better in quality than the preparatory work allows it to be. In other words the quality of the finished paint work is directly dependent upon the surface being free of indentations, scratches, dust and grease, and it also needs to be smooth and dry.

It is unlikely that the use of a robot could have substantially reduced the amount of rework required, unless the greater productivity possible from the use of an automated spray painting machine could permit an improved overall scheduling of the trade activities and a later commencement date for on site painting. The possibility also needs to be taken into account that *more* rework may be required using the robot in certain areas, than might be required if the work was done manually.

3.4 Evaluation

Both the site management of the main contractor and the painters agreed that a spray painting robot would not have been used on this project. The major reason given for this assessment was the quality control aspect with the painters inspecting the surfaces and performing appropriate rectifications and preparatory work as they progressed with the job. The difficulties associated with providing a clear and undisturbed work area for the spray painting operation was also a strong argument against using the robot, but was not the deciding factor in the final analysis. The site management acknowledged that it would be possible to rearrange the work sequences around the painting so that a spray finishing robot could be used, but stated that this would be an undertaking of such magnitude that the matter would need to be resolved at the top level of the company as a whole.

CONCLUSION

The assessment of benefits and organisational impacts indicates that the introduction of automated equipment may not always have positive net effects. In viewing the examples presented in this paper it is not difficult to understand the cautious approach to automation so often displayed by companies and project management in the construction industry [7].

The calculation of the costs and benefits of introducing robots onto construction projects showed that the inducement to invest in the robots can vary significantly from project to project.

However, from discussions with site managers and trade specialists, it is clear that it is not only the specific technical characteristics of a particular project that are important in determining the potential cost saving benefits likely to be associated with the use of automated equipment. Rather, the potential benefits to be derived will depend on a whole range of procedures practised in the company as a whole.

The cases examined in this paper illustrates the impact the introduction of automated equipment may have on some of those procedures, which may include:

- *The work organisation of employees whose tasks will be effected by the introduction of new technology:* The work organisation will influence the extent of labour logistics problem associated with bringing a new piece of machinery onto a site, and hence the potential savings to be realised through the increased productivity of some workers;
- *The sequencing of different phases of work on a site:* In the situations examined, the concurrent carrying out of more than one task within a defined area, such as placing reinforcing and constructing formwork simultaneously in the same slab area being

prepared for the concrete pour, precluded the use of automated machinery, for safety and scheduling reasons. In the assessment of the paint finishing operation safety and scheduling also emerged as strong issues against automation, although, in the final analysis they were not the deciding factors;

- *The use of subsequent tradesmen as a final quality control 'safety net':* Most projects to-day are under severe time pressure and this makes for compressed scheduling and complex work sequences. A common practise that has evolved in response to this situation is to use the team of a following trade to carry out the final quality check and also to effect minor corrective measures as necessary. In the case examining the possible impact of using a spray painting robot this proved to be the most important factor in the final decision not to use the robot.

The reaction of both management and tradesmen on these two projects has clearly indicated the importance of the approach developed in the assessment model. Their expressed view was that the consideration of any automated equipment for use on site should not be made for individual projects, but needed to be evaluated in the context of the work procedures and management policies for the company as a whole.

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