HOLISTIC-AUTOMATION OF CONSTRUCTION PROJECTS

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ABSTRACT

While advanced construction automation technology undoubtedly has great potential it has not as yet achieved any significant degree of industry use. This paper analyses some of the reasons for this and then proposes a new method for the creation of cost-effective field and project automation systems.

1. INTRODUCTION

Whilst construction robotics and other forms of advanced automation technology may have the potential to totally revolutionise the building and construction process, there has to date been virtually no serious commercial interest expressed by western type construction firms in this type of technology. The reason industry leaders give for this is that they see the systems being developed as being commercially non-viable.

The reasons that the technology is deemed non-economic by industry are complicated. While some factors lie on the technology developer's side there are a number of structural reasons and endemic practices in the mainstream construction industry that distort the economics of the issue and to a very large degree preclude much otherwise socially sensible and wise investment. These practices include much sub-system optimisation practice, a high level of projectisation and sub-contracting activity, much difficult placement of cost and profit centre boundaries, some unusual cash flow generating and project financing methods and modular job costing and discrete.activity based estimating methods. Many of these factors are intrinsically limiting to the development to construction robotics and other forms of advanced automation technology.

Set against this background, the focus of this paper is on the problem of how cost-effective field automation systems suited to industry's needs can be devised.

2. CONSTRUCTION AUTOMATION THEORY

2.1 FORMS OF AUTOMATION.

Within the context of the automation of mechanical action based activity, one can distinguish two distinct types of automation (a) hardware programmable automation and (b) software programmable automation. These may be considered to fall at two ends of a spectrum or continuum. An appreciation of the essential difference between these two forms of automation is important because only the latter type can deliver the benefits of automation to situations where small lots or one-off production runs apply[1,2].

Automation processes need not only occur at the overt manufacturing level but may also occur as invisible parts of some wider form (often intellectual type) activities or technologies[3]. A sample of a number of technologies that involve substantial in-built automation processes are listed in table 1 of Appendix A. Automation of intelligence gathering and analysis activity and/or the development of automated and computerised decision support systems also has great potential for appreciable productivity gains[3,22].

2.2 FIELD CONSTRUCTION AGENTS AND TECHNOLOGIES

In addition to traditional ideas of automation, some new notions of robotic and other forms of autonomous or automated field construction agent have been developed in recent times[4-5]. For the purposes of this paper, three distinctive types of field construction agent may be distinguished ie man type, man-controlled and autonomous (Fig 1). Autonomous types can be further divided into two sub-types - autonomous in structured or deterministic worlds and autonomous in interactive and dynamic worlds. The general concepts of autonomous and self-programming construction machines is explored further in References 5 and 6.

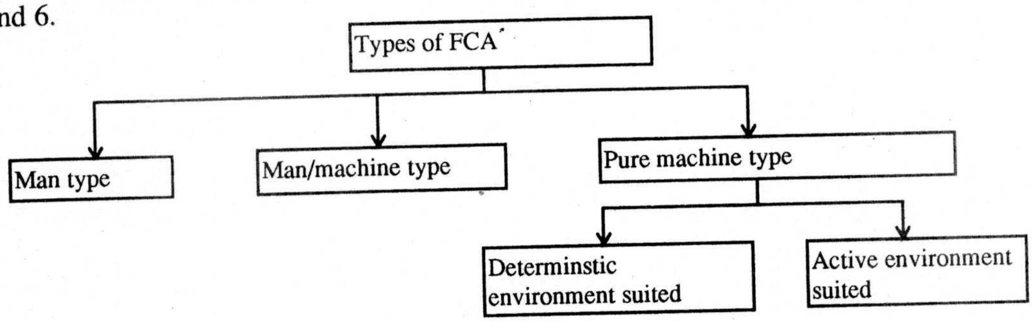

Figure 1 - A typology of field construction agent

The anatomy of various types of construction agent can be seen in relation to figure 1 and 2. In "man type systems" all functions are combined in the one biological unit.

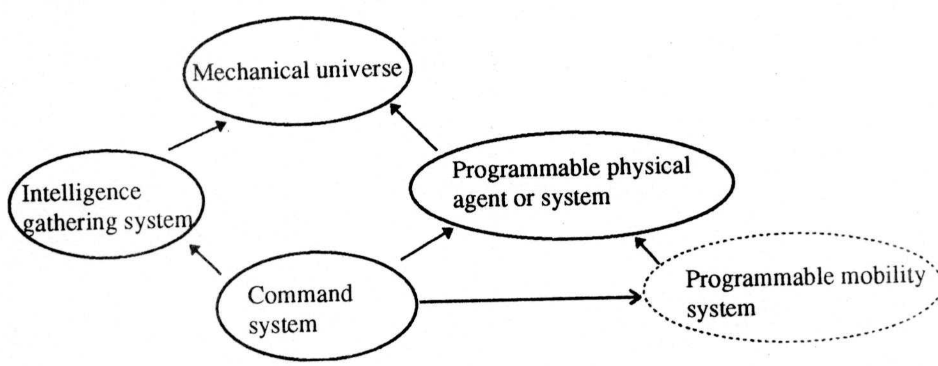

Figure 2 - A functional-module view of field construction agents

In "man/machine" and "mechanised systems" one can view the command and physical agent functions as being separately realised. These types of systems are often referred to as " operator in the loop" systems. In "deterministic robotic systems" no field intelligence gathering systems need be provided. In "full autonomous agent systems" all the functional modules need to be provided in one unit.

2.3 THE ECONOMIC APPEAL OF AUTONOMOUS FIELD TECHNOLOGIES

Fully autonomous construction systems have a significant economic appeal as compared to manual or man-in-the-loop methods because:

(a) Large direct wage and labour on-cost reductions can occur as a result of the total removal of the human from the control loop or his relocation to a supervisory role.
(b) Large performance differentials can be achieved through the deployment of power and force amplified physical agents.
(c) There is an improved capabilities for work performance- eg speed, accuracy, quality, size of workpiece, etc
(d) There are occupational health and safety and other direct worker benefit potentials.
(e) Autonomous systems give a potential for 24 hour per day operations.
(f) There is increased labour mobilisation flexibility.
(g) There are reduced skilled labour training and acquisitions costs[1].
(h) There are added-value potentials eg real time QA and QC, 100% QA and QC etc.

Autonomous field technologies can result in performance differences in kind as well as degree. However where one still has humans in the loop (ie mechanised automation) the full latent benefits of field automation will not develop.

2.4 THE COST STRUCTURE OF AUTONOMOUS FIELD TECHNOLOGIES

In relation to possibilities for the economic substitution of autonomous construction agents for manned or man-in-the-loop methods, the cost of synthesis of effective autonomous field construction agents is of vital significance. In the context of the technology available in 1996 however, advanced artificial intelligence command systems suited to the development of high IQ autonomous agents are beyond the state of the art. At the moment only quite low IQ AI systems are available but these can be embodied in quite low cost on-board computer systems. At the moment most of the cost of the synthesis of low IQ field construction agents lies in the manufacture of the basic mechatronic agent and in the provision of adequate sensing and data interpreting systems. High accuracy navigation and advanced vision systems, for example, are at the moment quite expensive and in many cases can limit any possibility for economic synthesis of a suitable construction agent. General purpose mobility bases are also expensive at this time. For the future however it is considered that all forms of sensing and information processing equipment will reduce in cost quite dramatically and the quality of AI systems will develop considerably. In terms of variable costs in use, deterministic robot systems programming can be expensive but systems for the cost effective programming of robotic systems are being developed (cf Ref 6). True problem solving robotics technology however is some decades or more away.

Since the current state of knowledge and technology only allows quite low IQ robotics systems and simple intelligence gathering system to be produced, advanced automation

technology can at the moment (irrespective of economic matters) only be applied to quite simple and routine types of construction task. Typically these tasks are those that humans find quite boring since they do not use all the capacities of the human mind. Activities however such as low level operator-in-the-loop control of machines, for example, can be handled by existing "smart" command systems. Autonomous construction agents can be developed for construction tasks such as the slow-speed roller compaction of earthworks embankments or for routine in-situ visual product inspection. Tasks that require appreciable problem solving abilities for their completion cannot at present be fully automated.
Despite these IQ limitations there are a number of tasks in construction that can be handled at present. Such activities as reinforcement placement and fixing, painting and sandblasting, concrete scabbling, water cart operation, concrete power trowel operation and many others can be automated. These are generally tasks that require only quite basic human psycho-motor skills functions to be automated[7].

Once the technical feasibility of field construction agent manufacture however can be established, matters of economic feasibility and commercial viability of systems arise. These viability matters involve the technology, competing construction methods and money.

3. METHODS FOR THE DESIGN OF COST-EFFECTIVE FIELD SYSTEMS

3.1 THE TRADITIONAL, TASK-SPECIFIC, METHOD

In the traditional method of construction automation system design, a task-centred, task specific or isolated activity approach to the problem is adopted. This method takes a specific task (such as "install ceiling tiles") analyses the specific task and task context and then seeks to mechanise the whole operation[8]. This method is the same as that used traditionally in factory and production engineering type automation situations. Unfortunately, sensible as it may seem, this method is typically doomed to economic failure within the context of construction for reasons that can be seen in Figure 3 and by virtue of the fact that:

i. High-technology solutions to construction problems tend to have high initial engineering and high tooling-up costs and most context specific construction tasks are much too limited in volume to support the requisite R&D and tooling up costs.
ii. The cost/benefits of the task alternatives are not properly measured if one takes the task as an isolated system and analyses it out of its context.
iii. Task centred and task specific automation methods tends to favour sub-systems optimisation and low-breadth-of-problem-formulation methods-engineering solutions[11]. Such procedures typically give very much less than optimal results.
iv. Mainstream construction industry practice requires methods pay-offs and pay-backs of investments within the lifetime of a single project. This investment environment is vastly different to that which prevails in manufacturing.
v. There is a major difference between the intrinsic economics of task-specific automation and task-general automation in relation to low volume production and jobbing type work.

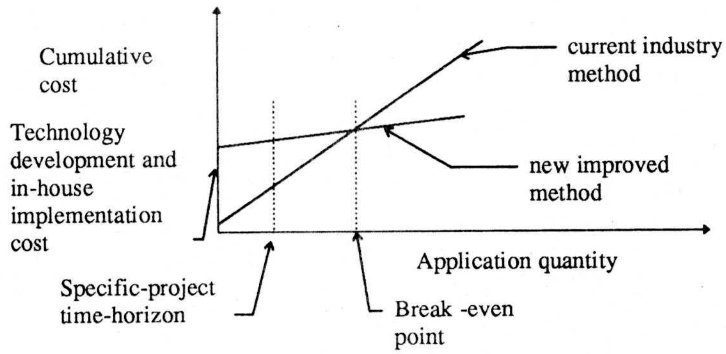

Figure 3 - Economic aspects of comparative-methods decision

Figure 3 shows a typical economic analysis graph for an automation-type technology competition situation that would occur on a construction site. A particular construction method (automated method or otherwise) will be deemed to be commercially viable if its economic break even point lies within the time horizon of the job. Otherwise it will not.

One reason why the task-specific automation approach typically fails is because most construction firms treat projects as distinct and separate "profit centres" and any investment made on a project in relation to R&D or plant investment has to pay-off within the lifetime of the project. If the project is small in terms of repetitive work volume then effectively no method that requires appreciable new equipment or tooling up costs will ever succeed.

Generally custom-made high-tech solutions to task execution fail either because the threshold cost of the proposed system is too high or else because the slope of the graph is too steep relative to both the project's decisional time horizon and/or to the current efficiencies of the best industry available competitive method.

The importance of figure 3 is due to the fact that methods comparison activities such as these are totally pervasive to construction projects[12]. Also it is clear that methods engineering is not only a technical problem it is also a techno/economic problem.

3.2 A NEW, HOLISTIC-PROJECT, METHOD

In contrast to the above task-specific method, which is intrinsically piece-meal and non-optimal[13], the writer would like to propose here an alternative approach to construction automation systems synthesis. This new approach is based on an holistic view. Through use of this method it is believed that considerably more cost-effective solutions can be developed as compared to the task-specific method. The method is called "holistic" because it requires that the totality of the *particular* project, the project environment, the client-system and the character and form of the available solutions technologies to be taken into account in solutions development. It also uses generic-task ideas rather than specific-task ideas and flexible technology compared to dedicated technology. Further, under this method:

- The project is treated as a "gestalt" and common denominator factors and synergies are sought between processes. Solutions to a number of process automation factors may be solved simultaneously and integrated solutions developed.
- The problem and the solution are allowed to interact and the full techno/economic problem is addressed across its full life cycle.

- The benefits of a method are considered to be realised across the life of the whole project rather than just locally and both mental-domain automation and physical-domain automation are considered concurrently. Worth is measured rather than merely cost.
- Multi-tasking technologies are encouraged and cost sharing between operations is sought.
- The project and its wider industrial context and automation environment are considered.
- Parallel or concurrent multi-front applications of disparate but complementary technologies is considered.
- Construction methods design is treated interactively with the permanent facilities design process and trade-offs across traditional profit-centre boundaries (such as between design and construction) are deemed essential.
- Inter-project and intra-project factors are considered in relation to the firm's broader corporate development plans and future mix of work[14].

The holistic or gestaltic method aims to provide more economically viable construction automation methods by (a) reducing the cost threshold of the method and by (b) increasing the amount of the benefits derived (Note: benefits amount is not explicit in fig 3 but can be considered as a negative variable-cost). By this means the break-even point can be brought within the life of a project and net benefits to a project (or series of projects) delivered.

4. SOME TECHNIQUES FOR USE UNDER THE NEW METHOD

4.1 TECHNIQUES FOR REDUCING THRESHOLD COSTS

One procedure that can be used to reduce the base cost of a technology is to spread the initial fixed cost of the technology across a number of within-project activities or profit or cost centres. This can be done, for example, by multi-tasking a piece of machinery over activities that may be otherwise individually costed, by sharing componentry across tasks or else by extending the use of a particular machine. This latter can be accomplished by increasing the machines scope of use through either the development of within project task repetition or by the development of machinery that can handle parameterised or variable tasks rather than specific or fixed tasks.

(a) Within single-project methods

More specifically, the initial threshold cost of an automation application can be influenced by amortising this cost over a number of applications domains within the confines of the job or by increasing the repetition use of the technique on the job. These conditions can be created by:

- Perception of generic tasks across the project and thence by organising the projects so that these tasks can be addressed collectively. This allows maximum utilisation of the technology.
- Multi-tasking the equipment eg a robotic concrete form cleaning system can be re-used later as a painting or tile setting robot.
- Using the same technology across a number of workfronts or disparate form activities on the same job (cf Table 1, Appendix A).

(b) Across-project cost distribution

The initial threshold cost of an automation application can be influenced by amortising this cost over a number of projects. These conditions can be created by:

- Deliberately adopting a task-general approach to technology development and basic R&D. This allows the distribution of tooling up costs, personnel re-training costs and so on across multiple projects and across a large set of operational activities.
- Use of software programmable concepts and flexible manufacturing systems ideas.
- Use of buffer mechanisms and such things as machinery leasing or in-house plant hire notions to distribute base system cost across time separated beneficial uses.

4.2 TECHNIQUES FOR EFFECTIVELY INCREASING WORK VOLUME

In fig. 3, the break-even point between competing methods is based on the total volume of a certain kind of work that is available within the confines of a particular project. By the use of clustering techniques and so on it is possible to increase the amount of within project repetition and hence generate large volumes of certain types of task. Alternately, one method of developing larger volumes is to develop machines that can handle parameterised tasks rather than specific tasks. The machinery scope of work then is taken over the total set of parameterised tasks rather than over a specific singular task. Alternatively, if action can be taken to rationalise and standardise tasks across sites then the volume of work for a particular machine can be increased.

4.3 TECHNIQUES FOR MINIMISING BASAL EQUIPMENT COSTS

Some techniques here are:

- Avoid custom designed-and-made equipment and instead try to spread the cost of the machinery across different applications bases through focus on general purpose and flexible machinery ideas. Use software programmable automation and flexible machinery philosophies. Use industry generic tools to reduce tooling-up costs.
- Adopt modular and built up systems approaches to equipment synthesis[18].
- Adapt existing on site or available equipment by application of add on modules[18].
- Adopt an agent rather than task or results focus and use a modular architecture for agent development and design multi-purpose construction agents and tools.

4.4 TECHNIQUES FOR MAXIMISING THE QUANTUM OF BENEFITS YIELDED

In fig. 3, it is clear that the project worth of a method is related to the slope of the graph. The more the benefits the more likely a method will be to be economic within the confines of a job. Some methods for maximising the project yield of benefits are:

- Aim for fully autonomous solutions rather than mechanised, tele-operated or man supported solutions. Look to capture the full time-stream of benefits.
- Aim for full longitudinal process automation[19] and use factory-to-finish notions.
- Provide suitable complementary technology such as simplified connectors[20] to allow best use of system and seek material savings through made-to-measure parts.
- Seek better process planning and coordination through automated IT systems[3].
- Streamline commercial interfaces through use of IT and electronic housekeeping technology and focus on client value adding activities[21].

4.5 TECHNIQUES FOR PROPERLY VALUING THE WORTH OF BENEFITS

As mentioned in the last section, the slope of the cost/worth line in figure 3 is important. How the net cost/worth of a method is measured influences the position of the viability point. If indirect benefits and costs are ignored then the true picture is distorted.

Automation methods generally yield good benefits in terms of cost, time, quality and response time as well as in less materials wastage. There are also in many cases significant OH&S issues, work place improvement benefits, and labour skills quantity, quality, availability and training issues[1]. Apart from direct cost, all these factors are somewhat indirect and intangible and are not measured in normal money-outlay-based job accounting systems[11]. These indirects and intangibles must be measured if one is to get a true picture of the worth of a technology in relation to a project. Some techniques here include:

use life time and holistic job costing systems in relation to the client's value function.Measure benefits accruing from system time response and system flexibility and from reduced project overheads and measure a method's demand on job infrastructure.

- Measure cost of waste and inter-process interference and congestion effects.
- Consider both upstream and downstream benefits and consequences.
- Measure weather sensitivity, quality, accuracy and process speed benefits as carefully as one might claim for price alterations due to contract variations.
- Use impact-incidence matrices for worth valuation within multi-beneficiary systems[10].

4.6 METHODS FOR SETTING UP THE BEST PRE-CONDITIONS FOR AUTOMATION

The potential for successful automation is majorly affected by the technical boundary conditions that are applied to the process or task to be automated and also to the context in which the exercise is embedded. To positively develop a climate for successful automation influence one can do such things as:

- Electronically integrate data and information across process and project stages cf CIC.
- Provide suitable infrastructure and complementary technology.
- Use systems-building methods where possible and look at full cost and benefit streams.
- Do process streamlining, rationalisation and standardisation[21].
- Transform unknown and unstructured systems into structured deterministic systems by provision of detailed geometrical site information and other data.

4.7 METHODS FOR SETTING UP A DECISION ENVIRONMENT FOR OPTIMAL CONSTRUCTION METHODS DECISION

Modern automation technology involves the use of a number of notions and techniques that are not common to site work. There is thus a job training and site education issue here. Also, job designers, project managers and estimators need hardware and software support in development of rapid methods for doing comparative method engineering studies based on notions of task-general automation and whole of life holistic job costing processes. The chances of automation introduction will be enhanced if computerised systems design tools can be developed that will highlight process interactions and do holistic job costings.

5. EXAMPLES OF THE USE OF THESE TECHNIQUES

Space within this paper does not allow for the development of many examples of the use of these techniques, but in high rise construction, say, all the variety of soffit anchor bolt installation operations which are currently required for under ceiling installation services and which are currently distributed in small lots across many trades can be collected together to give a large volume of similar work for an automated drilling machine system. (This however needs to be pre-done by the contractor at the time of work segmentation for subcontracting). Also if the automation task can be made deterministic by provision of a CAD model of the structure and through this the location of all the drill holes, then the cost of programming the data driven machine can be much reduced. To solve the physical drilling problem, a standard multi-degree of freedom mass produced industrial robot mounted on a general purpose scissors lift equipped AGV could be used. To reduce the basal cost still more, industry standard bolt-on navigation systems or positioning tool such as CAPSY could be used as mass produced modular components. To reduce the activity cost even more the same generic multi-purpose robotic arm could be shared with later paint spraying or tile setting activities on the same job or on-sold to other projects at the end of the job.

6. CONCLUSIONS

Whilst construction automation technology may have considerable latent potential, there is little hope that it will ever gain widespread industry acceptance until it can be proven to be both technically effective and cheaper in use than existing construction methods.

Because current automation attempts mostly founder solely in the economic domain there is a need to improve systems synthesis methods and economic evaluation procedures. In this paper two alternative methods of systems synthesis were developed. The first method is quite simple and analytic but tends to deliver non-economic solutions. The second method is more complex and creative but hopefully greatly increases the chances of automation systems being created that are economic within the confines of a particular project. If economically viable systems can be created in the present then very considerable long term benefits to the community and to the industry will undoubtedly develop.

7. REFERENCES

[1] Mair, G. M., "Industrial Robotics", Prentice Hall, 1988.

[2] Drozda, T. J. (ed) " Flexible Manufacturing Systems", Society of Manufacturing Engineers, USA, 1988.

[3] O'Brien J.B and Maidl B. " Automatic collection of Operational Data in Underground Construction" Tunnelling and Underground Space Technology, Vol 3, No.2, 1988 pp 141-151.

[4] O'Brien, J. B. "System Deployment Structures - A New General Form Of Robotic Construction Agent" 12th ISARC, Warsaw, 1995 pp 9-16

[5] Winter R.L., O'Brien J.B and Wakefield R. "A New Schema for the Engineering Design of Autonomous Agents in Non-Manufacturing Domains" in Forsyth, G. and Ali, M (eds) "Industrial and Engineering Applications of Artificial Intelligence and Expert Systems" 8th Intl Conf, Melbourne, June 6-8 1995 pp21-26.

[6] Winter R.L. and O'Brien J.B. "Self Programming Construction Machines" 13th ISARC. Tokyo 1996.

[7] Salvendy G, & Seymour W. "Prediction & Development of Industrial Work Performance" Wiley

[8] fFor example:- Hasegawa et Al " Description Method of Required Motion Specification for Construction Modularized Robot" 10th ISARC, Houston, Texas, 1993, pp 317-324

[10] De Neufville, R and Stafford, J.H "Systems Analysis for Engineers & Managers" McGraw Hill, 1994.

[11] Krick E. V. "An Introduction to Engineering & Engineering Design" Wiley 1969.

[12] O'Brien, J.B. and Compton R. "Field Studies of the Cognitive Processes involved in Construction Activity" 4th ISARC, Haifa, Israel pp 322-341, 1987.

[13] Jenkins G. M. & Youle P.V. " Systems Engineering" Watts (pubs), 1971

[14] Havers, J. and Stubbs F.W "Handbook of Heavy Construction" McGraw Hill, Chapter 7. on Equipment Economics by E.A. Cox.

[18] O'Brien, J. B. " Robotic action heads - New forms of attachment to existing construction machines" 11th ISARC, Brighton 1994 pp 691-700.
[19] O'Brien, J.B "Robotic systems for general concrete construction", Concrete-95, Intl conf. Brisbane 1995, Concrete Institute of Australia pp 787-792.
[20] Atkins B et al "Assembly techniques for large construction components" 11th ISARC pp 473-80. 1994.
[21] Koskela, L.and Sharpe, R. "Flow Process Analysis in Construction" 11th ISARC pp 281-288
[22] O'Brien J.B " Intelligence Work - A Neglected Aspect of Organisation and Management" S.Peer Memorial Publication on Construction Management, ed A. Shapira, Building Research Station, Haifa, Israel, Nov 1988, pp 56-63.

APPENDIX A - A PROJECT WIDE TECHNOLOGY APPLICATIONS MAP

GENERIC WORK AREA	*Advanced, computer integrated, real time surveying techniques*	*Smart and driverl ess vehicle technol ogy.*	*Robotic position ers handler s and manipu lators*	*Advanced process and system control technologies (including model based and GIS)*	*Automate d data capture, exchange and data communic ation (including Internet)*	*CAD and made to measure pre-fabricatio n*
Site office establishment	Yes					
Site clearing and demolition	Yes	Yes		Yes	Yes	
Site bulk earthworks	Yes	Yes		Yes	Yes	
Foundations	Yes		Yes	Yes	Yes	Yes
Pipe installation, & drainage pipework	Yes	Yes	Yes	Yes	Yes	Yes
Crane, hoist and other major site systems setup				Yes	Yes	
Main structural frame	Yes		Yes	Yes	Yes	Yes
Building cladding and external enclosure	Yes		Yes	Yes	Yes	Yes
Interior plumbing and pipework	Yes		Yes	Yes	Yes	Yes
HVAC	Yes		Yes	Yes	Yes	Yes
Lifts and mechanical services	Yes		Yes	Yes	Yes	Yes
Interior fitout	Yes	Yes	Yes	Yes	Yes	Yes
Electrical services				Yes	Yes	
Commission &test				Yes	Yes	
Cleaning & cleanup		Yes	Yes	Yes	Yes	
Landscaping		Yes	Yes	Yes	Yes	

Table 1 - An example technology applicability matrix for a major building project