

ECONOMIC APPRAISAL AND RISK ANALYSIS OF CONSTRUCTION AUTOMATION

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**A thesis submitted to Napier University,
in partial fulfilment of the requirements for the
Degree of Doctor of Philosophy**

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Abstract

This thesis sets forth the results of research into the economic appraisal and risk analysis of construction automation investment. The research, development and use of automated plant and machinery for the construction industry has become a reality. The valuation of construction automation is inhibited by the inadequate appraisal techniques. Furthermore, the dominant role of the plant hire industry has been ignored within existing valuation methodologies.

An international review of existing prototype and manufactured technologies is presented. Unsuccessful technologies are highlighted and systems which are providing valuable operational advantages to the international construction industries. A selective study of Japanese main contractors using focus group interviews highlighted existing capabilities and identified key directions for future research. The focus groups provide a qualitative analysis of the limitations of historical research and ongoing construction automation operations.

The inadequacies of valuation procedures are confirmed through a critical review of the existing valuation methodologies. Discontinuities within the existing literature influence the development of a generic financial risk analysis model and the application of real option pricing theory to the strategic valuation of construction automation. Specifically, the dominant role of the plant hire industry is incorporated through the valuation of automated technology from the perspective of a plant hire company. A probabilistic financial risk analysis model is developed to perform a hypothetical financial risk analysis. Furthermore, the application of real option-pricing theory to the valuation of construction automation investment is presented. Timing, learning, abandonment, strategic growth and switching

option scenarios are described within the context of construction automation valuation and worked examples are presented. Finally, the limitations and validation of such valuation models are outlined. The thesis provides insight into the potential strategic value of construction automation.

Declaration

This thesis is submitted to Napier University, Edinburgh for the degree of Doctor of Philosophy. The work described in this thesis was carried out under the supervision of Dr Sam Wamuziri and Dr Ian Smith. The work was undertaken within the School of the Built Environment, Napier University. In accordance with Napier University regulations governing the degree of Doctor of Philosophy, the candidate submits this thesis as original unless otherwise referenced within the text. During this period of research the following papers have been presented and/or published:

1. TAYLOR, M.D., WAMUZIRI, S.C. & SMITH, I.G.N. (2003) Automated Construction in Japan, *Proceedings of the Institution of Civil Engineers, Civil Engineering*, 156 (1), 34-41, ISSN 0965 089 X.
2. TAYLOR, M.D. & WAMUZIRI, S.C. (2002) Strategic construction mechatronics valuation: a real option-pricing approach, *Journal of Financial Management of Property and Construction*, 7 (2), 75-90, ISSN 1366-4387.
3. TAYLOR, M.D. (2001) Modelling the value of construction mechatronics investment opportunities, *ARCOM Doctoral Workshop: Simulation and Modelling in Construction*, Edited by Professor Akin Akintoye, 26th October, University of Edinburgh, 3-6.
4. TAYLOR, M.D. (2001) *Can we automate construction?*, Paper presented to the Institution of Civil Engineers East of Scotland Association, Winner of the East of Scotland Association Young Engineer's Paper Competition, Winner of the 2002 Joseph Miller prize.

5. **TAYLOR, M.D., WAMUZIRI, S.C. & SMITH, I.G.N.** (2001) Strategic mechatronics investment: understanding the managerial options, *17th Annual Conference of the Association of Researchers in Construction Management*, September 5th – 7th, University of Salford, Manchester, 2, 333-342.
6. **TAYLOR, M.D., WAMUZIRI, S.C. & SMITH, I.G.N.** (2000) Analysis of risk in construction automation investment, *17th International Symposium on Automation and Robotics in Construction*, September 18th - 20th, Taipei, Taiwan, 109-114.
7. **TAYLOR, M.D.** (2000) *Automated Technology in UK Construction and Civil Engineering*, Research poster presented at the National Week of Science, Set for Britain reception, hosted by Robert Jackson MP, March 19th, House of Commons, London.

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Chapter 7

There are no tables in Chapter 7.

'The robots will make bricks and houses for us.'

Karel Capek: Rossum's Universal Robots 1923

CHAPTER 1

INTRODUCTION

1.1 General introduction to construction mechatronics

The word robot originates from the Czech word *robota*, meaning forced labour. In 1920, Karel Capek used the term in a play entitled *Rossum's Universal Robots* (Capek 1923). The play depicted a scenario where society was dependent upon mechanical workers. These conscious automatons, which could perform mental and physical tasks, eventually led to the downfall of society. In 1941, the science fiction writer Isaac Asimov first used the term robotics to describe the technology of robots and predicted the beginning of a powerful robot industry. Asimov's prediction has materialised and there has been extensive expansion in the development and use of industrial robots.

In 1956, George Devol and Joseph Engelberger formed the world's first robot manufacturing company. Unimation Incorporated developed the first applied industrial robot. The robot was employed within a General Motors factory in New Jersey (USA) to extract die-castings. The process is one in which molten, non-ferrous metals or alloys are forced into separable metal moulds called dies, resulting in well-finished parts. The dies had to be cleaned, the pressure maintained, and later water-cooled. Managing these machines was a hazardous occupation, with constant exposure to heat, noise, obnoxious fumes and the possibility of physical injuries. Unimates were also developed to perform spot welding on automobile bodies, both tasks being hated assignments for human operatives.

There has been rapid expansion in the development and application of robots due to improvements in microelectronics technology. Car manufacturers have contributed to growth through substantial capital investment in automated assembly lines. Modern

industrial arms have increased capability and performance through controller and language development, improved mechanisms, sensing and drive systems. Additional robot applications include painting, plastic moulding, forging, palletising, printed circuit board production, master-slave surgery and lunar exploration. Robot manufacturers are not limiting their products to industrial uses. Recent robot applications include, housework, gardening and entertainment. In comparison with industrial manipulators, service robots require increased mobility, portability, limited artificial intelligence and adaptability to widely varying operations and dynamic environmental conditions.

In 1978, the Japan Industrial Robot Association (JIRA) under the direction of the Ministry of International Trade and Industry (MITI) initiated the first known research into the application of automated technology to construction project operations (Cousineau & Miura 1998). The project was directed by Professor Hasegawa of Waseda University Systems Science Institute. Professor Hasegawa later founded the WASCOR (WASeda CONstruction Robot) research group.

During 1983, the Shimizu Corporation introduced the world's first programmable construction robot - SSR-1. They claimed that the machine was 20% more productive than skilled human operatives and the system liberated workers from dirty and hazardous working conditions (Anon 1983). The system was a programmable robot for applying fireproofing material onto structural steel and resembled a traditional manufacturing manipulator. Figure 1.1 shows the rolling stock, manipulator arm and control computers of the proceeding prototype system SSR-2. SSR-2 was applied within the construction of the 40 storey Toshiba headquarters building in Shibaura, Tokyo.

Warszawski (1985) separated building activities into basic components and specified the performance requirements for early prototype construction robots. Conceptual descriptions of four categories of construction robot were defined from these

performance requirements. Figure 1.2 shows the four categories of prototype construction robot; the assembling robot, the interior general-purpose robot; the floor-finishing robot and the exterior wall-finishing robot.

By 1989, the Takanaka Corporation was applying the Roof Push-up construction method to the construction of the twelve-storey Yanagibashi Mitsui Building in Nagoya, Japan. The method applied manufacturing production principles to the construction of multi-storey structures. The construction procedure was initiated with the assembly of the enclosed mechanised construction equipment. This was followed by the construction of the roof structure, then the construction of the lower floors, which were then pushed up after construction by hydraulic jacks. The enclosed construction environment provided protection from adverse weather conditions and the overall integration of construction techniques enabled more effective construction work. Figure 1.3 provides an artist's impression of the Roof Push-up system concept.

In 1991, the Obayashi Corporation successfully applied the Automated Building Construction System (ABCS) to the construction of the Riverside Sumida Bachelor Dormitory, in Tokyo, Japan. The system revolutionised the high-rise construction process. The system resembled an automotive factory where automated material manipulators were employed to erect and weld the steel super-structure, install the pre-cast concrete floor panels and install curtain wall panels.

The ABCS system creates a less hostile and more structured environment for the application of automation. With the use of the ABCS system, the Obayashi Corporation claim to be progressing towards a reduction in site labour, improved construction quality, increased site safety, weather unaffected working conditions and minimal environmental impact (Evans 1996). The Shimizu Corporation, Taisei Corporation, Kajima Corporation, Maeda Corporation and Fujita Corporation have also developed similar technology and are claiming similar benefits and potential economic advantages.

Advantages frequently attributed to construction automation include increased productivity, more efficient use of materials, better product quality, improved safety and shorter working hours for operatives. Despite claims of the high quality workmanship by human operatives, automated systems typically perform with less variability than human workers, resulting in greater consistency and control of production quality.

The following drivers support the utilisation of automated construction plant and machinery:

- possibility of direct labour replacement;
- a lesser dependence upon casual workers;
- the ability to counteract labour shortages;
- increased productivity;
- increased site safety -avoidance of work in high, unpleasant and dangerous locations, safer operation of machines;
- increased quality;
- greater consistency in the outcome of the work;
- greater control over the production process;
- competitive advantage through lower input costs; and
- improved corporate image and international competitiveness.

Operative safety is a primary driver for automating construction project operations. Construction automation provides the opportunity to relieve humans from repetitive, hazardous and unpleasant labour activities. For example, tele-operated construction systems remove operatives from the immediate workplace, thus safeguarding them from the hazards associated with the majority of construction operations.

Construction site accidents may affect plant, equipment and people and thus threaten strategic project objectives. Every accident, whether or not it involves an operative, will give rise to a cost and a consequence. The cost of material damage, delays caused by repair work and waiting for replacements may have detrimental effects on the quality and performance of the finished product (Charlton 2000). Automated construction technology may present an acceptable means of minimising the risks associated with construction accidents. The utilisation of automation may remove the strain of potentially debilitating operations and human skill will be concentrated upon alignment, monitoring and defect detection. Automation will place greater emphasis upon knowledge-based work and technical skill rather than physical work.

The successful implementation of automated construction technology is inhibited by the following technological, design, planning, economic and organisational issues:

- fundamental difference between manufacturing facility and construction site generates problems (physical strength, payload weight, positional accuracy, force feedback, sensors and mobility);
- sensor and control technology must be developed to facilitate autonomous application and to withstand the harsh construction site environment;
- the practical application of multi-task systems is limited due to the complexity of on-site work environments;
- the cost of developing and implementing technology and the justification of the economic viability with the risks properly considered; and
- state of fragmentation within construction industry - responsibility and control split, innovation stifled from no one organisation taking overall charge.

A recent catalogue of Japanese construction robots reported that Japan has developed over 550 types of construction robot (Council for Construction Robot Research 1999).

Construction automation research, development and implementation has become a powerful marketing tool and a source of competitive advantage between rival Japanese construction companies.

Owing to a rapidly ageing workforce, Japanese general contractors and machine manufacturers are advancing the capabilities of automated construction technology. The economic recession within Japan has led to a declining demand for labour services within the construction sector. However, the shortage of skilled labour within Japan is rapidly outpacing the reduction in demand. Automated technology is perceived as a practical solution to minimising the effect of any future skilled labour shortage.

The demand for construction robots within the UK construction sector will be signalled by the quantity of problems that the technology might solve; whether these problems are widespread; and, if the problems are widespread, whether they are growing and whether they recur (McGrath 1997).

Resulting from sector growth, the UK construction industry is expected to experience a considerable skilled labour shortage in both traditional and new skill areas (Mackenzie *et al* 2000). The potential shortage of skilled operators and maintenance staff raises the need for occupational and technical training to develop the required work-force expertise. Necessary expertise will include machine maintenance, improved planning and scheduling and operational training. Many operatives may be displaced from existing positions and retrained to assist in supporting automated technology. Investment in imported automated construction technology may present a financially viable means of mitigating any future UK labour shortages.

High capital expenditure may not be appropriate for contractors who wish to maintain their fixed capital at a minimal level. Construction robots may be perceived as less flexible and more expensive than traditional plant and machinery. The most befitting

method of implementing construction automation will be through the UK plant hire sector. Therefore, machines may be utilised by contractors with minimal capital expenditure and maintenance and repair requirements will be borne by the plant hire firm.

The UK civil engineering and construction industry is fragmented in its advances in the application of automated construction technology (Thompson 1998). Conservatism within the UK industry stems from a limited knowledge of the technology in question. The rate of innovation lags behind most other sectors, and appears to be falling further behind (Winch 1998). However, recent research suggests that innovation occurs consistently throughout sectors of the construction industry and that construction companies are generally interested in innovative technologies and designs, whether relating to materials, components, systems, methods, equipment, management, or other related areas (Slaughter 1998).

Innovation stems from two forces: market demands and progress at the technological and scientific frontiers (Tatum 1987). Presently, the demand for automated construction technology within the UK construction sector is questionable. However, the scientific frontiers seem to be progressing as more practical and cost effective solutions to construction related activities are becoming available.

1.2 Research domain

Extensive international research and development has been conducted within the field of construction automation and robotics over the last 25 years. Many prototype technologies currently exist in conjunction with a broad range of established automated technologies. Specifically, there is a need to examine the post-innovation and post-implementation developments. The Japanese general contractors currently lead the field of construction automation in relation to their on-site achievements. However, the 'big-

six' general contractors have re-directed their research efforts and changed the evolution of construction automation.

An introductory literature review is presented in chapter two of this thesis, with specific literature reviews presented within each chapter. It has been reported that widespread ignorance in the civil engineering industry is the reason for stunted development (Thompson 1998). The UK industry requires the demonstration of economic feasibility, increased safety, system reliability and increased productivity. A guarantee of performance and financial benefits is required prior to widespread deployment. The technology highlighted within this research may not immediately replace human labour on construction projects, but will greatly enhance construction operations through increased safety, productivity and quality.

Financial risk is of prime importance to the construction industry. Assessing the feasibility of transferring existing Japanese technology to UK construction sites will incorporate analysis of the perceived tangible and intangible benefits. The deficiencies in current appraisal methodologies have manifested themselves so that further research is required to determine the true strategic value of construction mechatronics investment opportunities.

1.3 Objectives of the study

The principle objectives of this research were to enhance the understanding of existing technological capabilities, the associated investment risk and methods of strategic valuation for automated construction technology. The work is primarily aimed at construction contractors and plant-hire organisations who may be considering using the available technology.

The research concentrates initially on assessing international developments in the research, development and application of construction mechatronics. Through the application focus group the attitudes, experiences and directions for future research are elicited from Japanese construction industry professionals. Finally, the research focuses upon economic valuation, investment risk and strategic valuation. In particular, the research develops a generic risk analysis model and presents the application of real option pricing valuation theory to construction automation investment.

In order to achieve the research aim, the following objectives were established, and duly satisfied, as the research was implemented:

- I. to critically investigate the existing state-of-the-art technology and assess current capabilities;
- II. to conduct qualitative sociological research regarding the pertinent issues challenging the leading international developers, machine manufacturers and early adopters;
- III. to review existing investment appraisal methodologies and highlight their deficiencies;
- IV. to develop a generic financial risk analysis model to structure and quantify the uncertainty surrounding construction automation operating and ownership costs; and
- V. to apply real option pricing theory to the appraisal of construction automation investment and develop real option valuation models for selected investment flexibility options.

1.4 Outline of the thesis

This section outlines what is included within the thesis. A brief summary of each chapter is presented. A total of seven chapters with references and an appendix are included in this thesis.

Chapter 2 Review of construction automation investment valuation

Chapter two provides a review of the existing theoretical and empirical work concerning the economic valuation of construction automation investment. A review of the mathematical foundations relating to investment appraisal, construction automation economics, investment risk and strategic valuation is presented. Previous investigations and methods of investment valuation are critically reviewed. Discontinuities within the existing literature are identified and are used to form the basis of the present study.

Chapter 3 The state-of-the-art technology

Chapter three presents a succinct and quantitative review of construction automation technology. The research highlights the deficiencies associated with specific technologies and highlights those technologies, which are providing valuable operational advantages to the international construction industry. Focus group studies provide an in-depth and qualitative insight into the present status and future direction for Japanese construction mechatronics research, development and deployment. Specifically, the results examine the deployment of existing technology and the benefits and limitations of this technology. Directions for future research appear to have altered due to recent developments in automation technologies.

Chapter 4 Construction automation economics

Chapter four provides a detailed examination of the pertinent issues relating to the economic valuation of construction automation technology. An overview of Japanese research and development is presented. Tangible and intangible costs and benefits are highlighted and explained in detail. Finally, the research concludes that the economic considerations of machine manufacturers, construction plant hire organisations and construction contractors must be segregated so as to apportion the correct costs and benefits to the appropriate organisation. This is a distinct step forward from valuing construction automation investment without considering the role of the plant-hire industry. This model forms the basis for the following chapters.

Chapter 5 The Analysis of Construction Automation Investment Risk

Probabilistic risk analysis has been incorporated into a generic construction automation appraisal model to perform a financial risk analysis on a hypothetical investment opportunity. All input parameters were described using probability distribution functions and were sampled randomly using Monte Carlo simulation. The risk incorporated in each analysis was presented as the standard deviation of investment returns. The probability of net present value (NPV) < 0 (i.e., investment rejection) was also evaluated.

Chapter 6 Real Option Analysis of Strategic Construction Automation Investment

The application of real option-pricing theory to the valuation of construction automation investment is presented in chapter seven. Timing, learning, abandonment, strategic growth and switching option scenarios are described within the context of construction

automation valuation and worked examples are presented. The study provides insight into the strategic value of construction automation investment.

Chapter 7 Conclusions and recommendations for future research

A global summary of this research project is presented. Following this, conclusions drawn from each chapter are also presented to provide a summary of the key findings, which have risen from each strand of the research project. In this way the individual chapters are combined to represent the whole thesis and the overall research topic. Future work is suggested so that the current research may be further developed. It is suggested that full-scale trial demonstration projects be used to facilitate scientific work studies in order to compare the efficiency and productivity of automated technology versus human labour alone. The efficiency of the machines will be evaluated and benchmarked, using key performance indicators, against traditional construction techniques. Following on from these scientific work-studies, there are requirements for an internet based implementation, repair and maintenance cost database. This may assist contractors and plant-hire organisations in assessing the efficiency and cost effectiveness of the available construction mechatronics technology. The thesis is completed by the list of references and appendices containing seminal research and the publications authored during the programme of this research.

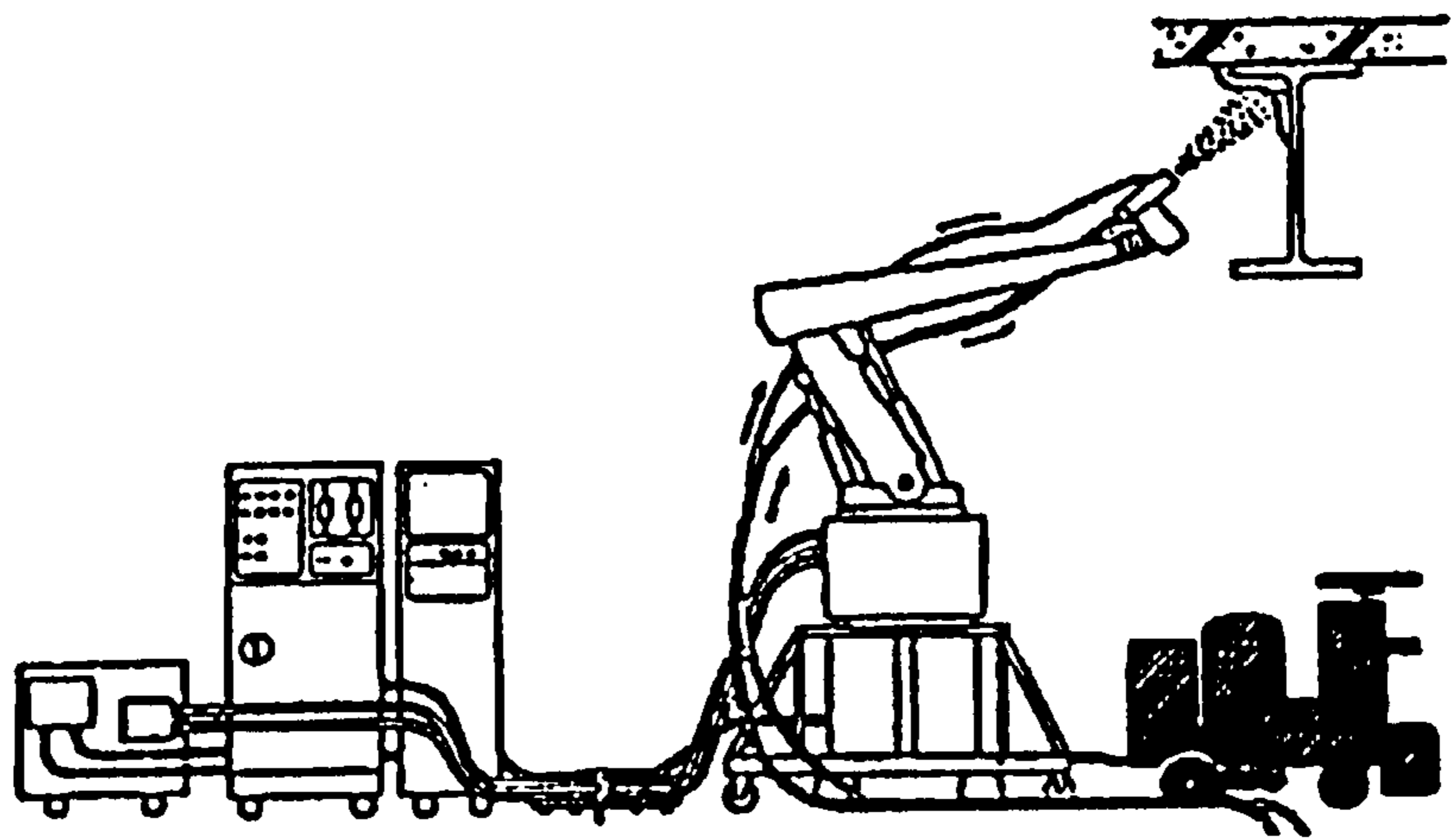


Figure 1.1: SSR-1 system configuration
 Courtesy: Shimizu Corporation

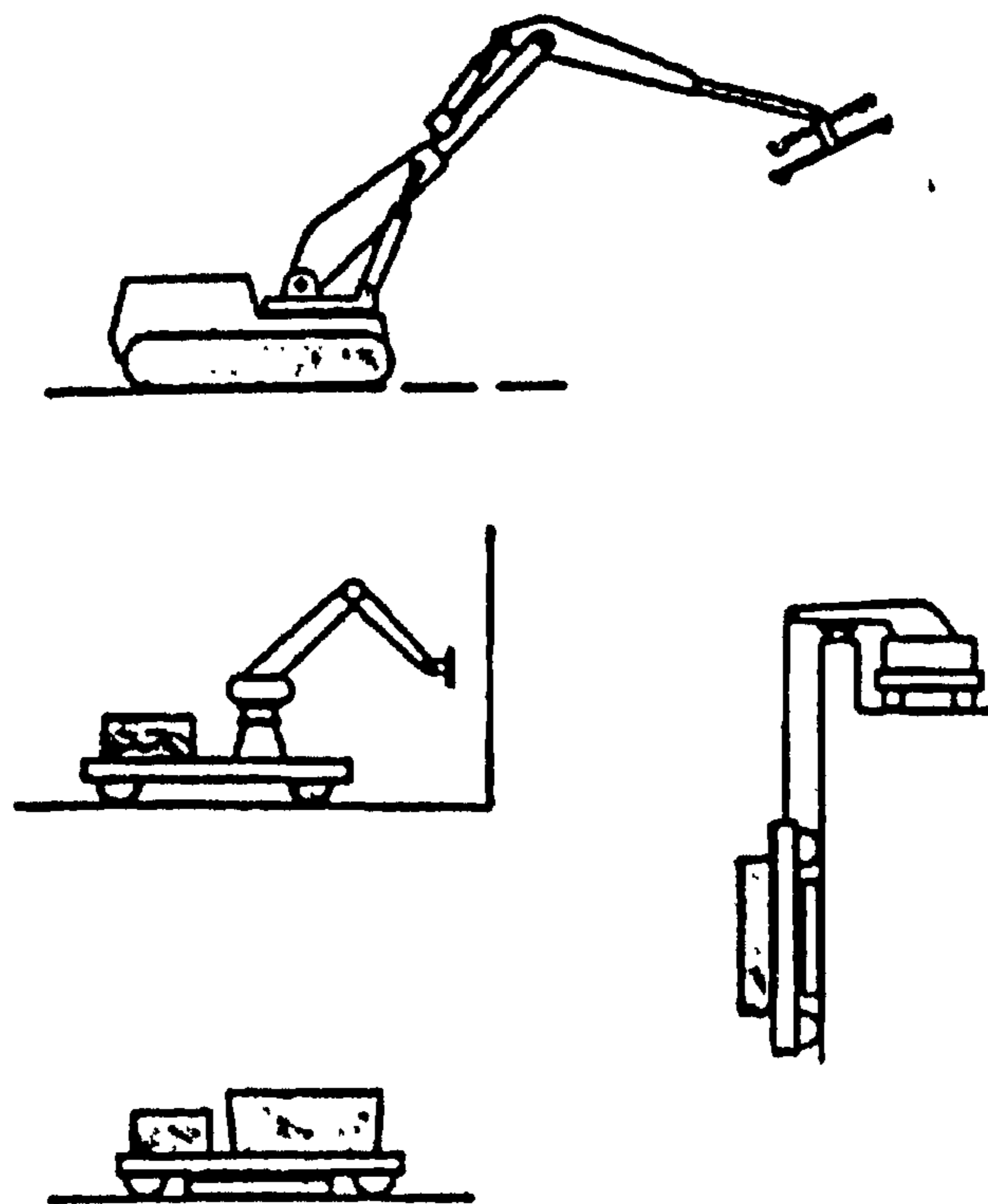


Figure 1.2: Categories of prototype construction robot
 Source: Warszawski 1985

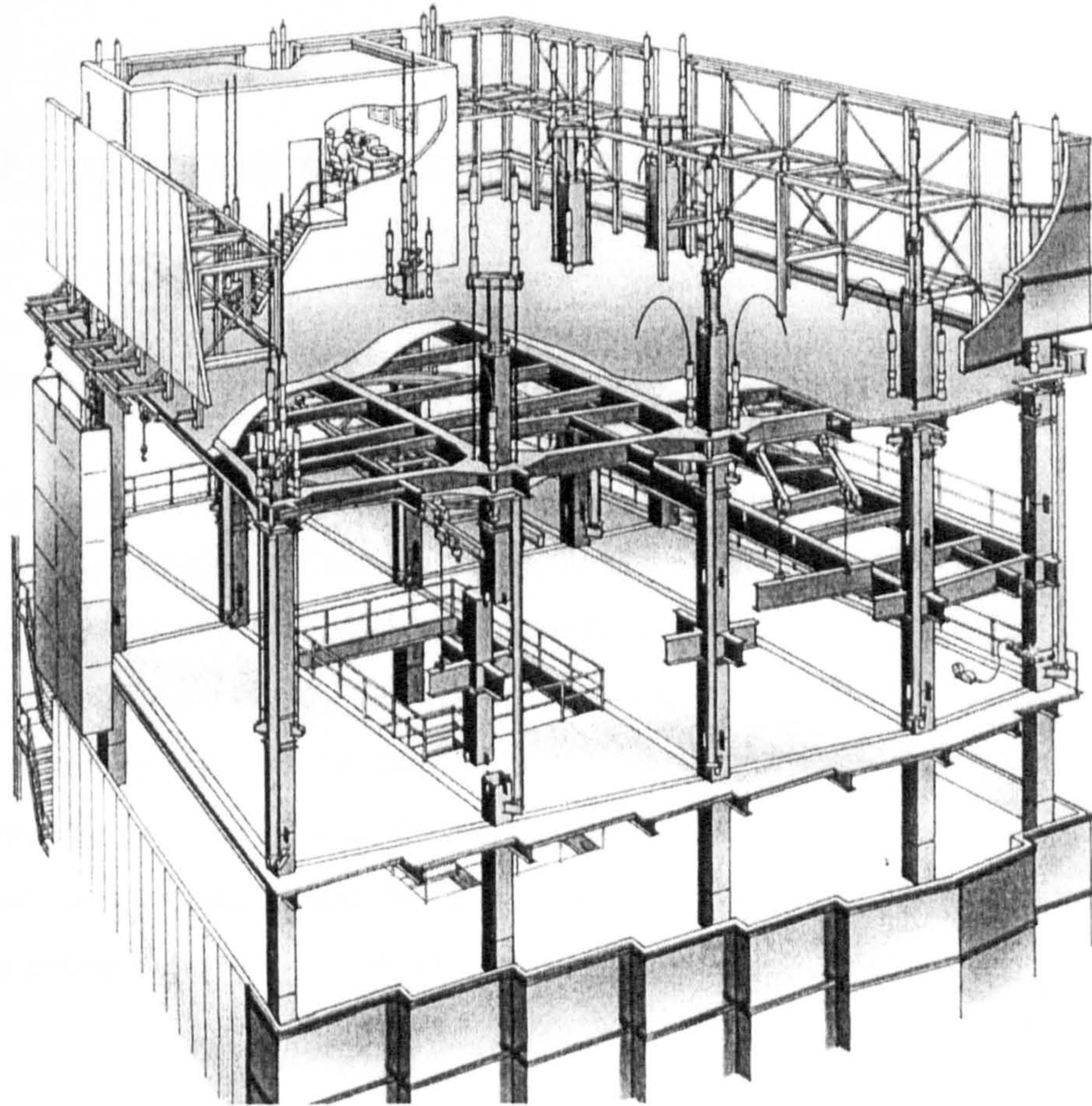


Figure 1.3: Roof Push-up automated high-rise construction system concept
Courtesy: Takanaka Corporation

CHAPTER 2

REVIEW OF CONSTRUCTION AUTOMATION VALUATION

2.1 Introduction

Chapter one set out the objectives of the thesis and provided a brief introduction to the problems to be tackled. This chapter provides a background to the problems by reviewing previous work relating to construction automation economics, investment risk and strategic valuation. Furthermore, this chapter aims to highlight gaps within existing literature and provide reasoning for the methodological approach assumed within this thesis. Throughout, the approaches and methodologies used by previous researchers are detailed, the aim being to identify where previous work has presented a lack of attention to pertinent issues and their effects.

2.2 Construction automation and robotics: existing capabilities

There has been a considerable volume of literature reporting the testing and evaluation of construction automation and robotics technologies. Of the vast array of single task systems developed since the early 1980's, a small selection of systems have, and continue to be, deployed on operational construction projects. Cousineau and Miura (1998) concluded that construction robots have not achieved the expected economic gains relating to increased productivity, shortened construction periods and reduced cost. Furthermore, they describe a lack of manpower reduction and the creation of new specialist jobs that require knowledge of various trade-work and the ability to set-up and operate these new machines. This has apparently led to the research and development of fully automated construction systems. The extent to which these technologies are

used on today's construction and civil engineering projects requires further investigation.

Ueno (1994) reported that the next generation of construction automation and robotics has diverged from single-task systems into three streams. These are low cost tele-operated systems, intelligent robots and construction automation systems. Furthermore, he commented upon the next generation of construction automation technology not incorporating sophisticated automated or robotised systems due to their cost increasing linearly with their level of automation.

Cusack (1992) recognised that innovations are rarely fully developed when they are first introduced and that their full economic significance depends upon the continued development following their introduction to the market place. Therefore, there is a need to investigate the post innovation improvements that have been undertaken following the implementation of construction automation and robotics technologies.

2.3 Construction automation economics

Within existing literature there has been considerable debate over the identification and allocation of the costs associated with the research, development and deployment of automated construction technologies. In the volatile and conservative construction environment, the economic benefits of construction automation and robotics must be clearly presented to management, even when not easily quantifiable, to justify the significant long-range commitment to implementation (Warszawski 1999). Bearing this in mind, the uncertain economic costs and benefits associated with such strategic commitment must be incorporated within any economic feasibility study. However, there is considerable uncertainty surrounding the intangible and tangible economic costs and benefits associated with the deployment of innovative construction plant, which has yet to be widely accepted and utilised by construction and civil engineering contractors.

According to Warszawski and Navon (1998), the intangible benefits of construction automation and robotics (improved safety, higher quality and dependability) have prominent economic value through the avoidance of quality defects, accidents and work stoppages. They follow that construction robots have the best chance of implementation where special economic premiums are placed upon such intangible assets.

Kangari and Halpin (1989) described a methodology for the feasibility analysis of robotics in the construction industry, which incorporated a need and technology based feasibility. The need based feasibility described factors, which constituted a demand for the available technologies. These included:

- labour intensity of construction processes;
- vanishing skills;
- high dexterity, precision and skill requirements;
- repetitiveness of tedious and boring construction processes;
- processes critical to productivity; and
- unpleasant, dirty and physically hazardous construction processes.

In conjunction with the need based feasibility, factors determining the technological demand feasibility were:

- sensory requirements;
- control software requirements;
- control hardware requirements; and
- end-effector requirements.

The above factors describe the various technology demand and supply issues that will determine the overall economic feasibility of implementing construction automation and robotics.

The feasibility of construction automation and robotics employment has previously been assessed through comparison of the robot's value with the estimated cost to the user. Warszawski (1986) calculated this value as a present value of net savings (benefits less maintenance, operation and transfer costs) over its economic life cycle. This technique has two fundamental limitations:

1. the use of discounted cash flow appraisal techniques does not allow for investment flexibility and the possibility of the investment parameters changing due to external circumstances; and
2. attributing operation and maintenance costs to the end user ignores the possibility of expensive and utilisation rate sensitive plant being hired via specialist plant-hire organisations or existing plant-hire organisations which have diversified into construction automation and robotics technologies.

Naoum (1994) concluded that firms investing in robotic systems must consider their degree of plant dedication and specialisation, since investment returns can only be maximised if the plant approaches full utilisation over its economic life. This highlights the importance of high rates of utilisation for specialist plant and machinery, but also implies that only specialist sub-contractors will be able to provide these high levels of deployment. However, the uptake of such technologies by plant hire organisations may facilitate the requirement for high rates of utilisation to secure adequate investment returns.

There is a broad range of economic uncertainties that surround the decision to deploy automated construction technology. These must be assessed and quantified, where possible, in order to conduct a feasibility analysis of any such technology. Specifically, further research is required in the segregation of these uncertainties and their assessment in relation to the appropriate construction industry party. The following sections examine the existing theoretical work regarding the economics of such technologies. The overall aim being to highlight the importance of attributing the associated costs and benefits to the appropriate organisations.

2.3.1 Theoretical work on construction automation economics

The following sections present an overview of the seminal work concerning the economic appraisal of automation and robotics for the manufacturing sector and specifically for the construction industry.

2.3.2 Kangari & Halpin: potential robotics utilisation in construction

Kangari and Halpin (1989) identified the major factors in the automation of construction processes as need, technology and economic feasibility. They described the basic economic benefits of construction automation and robotics as: productivity improvement; quality improvement; and savings in skilled labour requirements.

Productivity was defined as the ratio of output to input, typically given as units produced per man-hours. In order to derive whether an increase in productivity is attainable, a comparative study of the existing construction technique and the automated system should be undertaken. Importantly, if historical work productivity data is not available then these values must be obtained through experimentation. However, there is considerable cost associated with the collection of such data. If the construction

operation is to be successfully automated then the expected increase in productivity should absorb the cost of implementation.

2.3.3 Najafi & Fu: economic evaluation of robots in construction

Najafi and Fu (1992) presented a justification for introducing automation in light of the possible reduction in health hazards, increased work productivity and labour cost savings. They highlighted that the success of automation in the construction industry depends upon the value to the construction contractors in comparison to traditional construction procedures. In their cost-benefit analyses, they separate the associated costs into two sub-divisions: capital costs and operating/maintenance costs. Major capital costs include the purchase of hardware and software, initial training of operating personnel, adaptation of the work environment to facilitate robot implementation, special work tools, accessories, monitoring and control equipment. In order to compare like-with-like, they recommend that costs are converted into unit costs for a given building task performed by both traditional and automated construction techniques. An economic valuation of an automated system for the construction of interior wall partitions is presented. In a direct unit comparison of the manual construction technique and the application of the automated erection system, they conclude that the automated system reduced the unit installation cost. However, this comparison was undertaken for a prototype system (WALBOTS developed by MIT) and on-site trials would be required to validate this outcome.

2.3.4 Bennett, Flanagan & Norman: economic impact of robot

Bennett *et al* (1987) presented the results of a 12-month study of the Japanese construction industry. A primary objective of their research programme was to investigate the motives for construction automation and robotics research and development. The principal motive for undertaking such research seemed to be a continuing shortage of labour on building sites capable of undertaking the heavier and

wet trades. They concluded that the average age of the labour force was increasing and that it was proving increasingly difficult to attract young people into the industry. The short-term hope was that robots would fill the gap created by these labour shortages. However, they predicted that due to declining demand for construction services (continuing economic recession), declining supply of site operatives and continued development of such technology there would inevitably be an export drive to reduce the technologies net effect upon domestic unemployment. Figure 2.1 depicts this prediction graphically and indicates that following the development of successful prototype technologies and their subsequent mass manufacture (t_1 to t_2), there will be an export drive for these developed construction robots.

However, the Japanese construction industry has yet to experience any rapid uptake in the deployment of automation and robotics. Furthermore, it remains to be seen whether the predicted mass export drive will materialise. This research has highlighted the need to investigate the present technological capabilities of the Japanese construction contractors and machine manufacturers with particular reference to their export strategies. Specifically, the labour reduction capabilities of existing technologies must be examined.

2.4 Construction automation investment uncertainty and risk

In a review of literature published between 1960 and 1997, Edwards and Bowen (1998) concluded that technical risks not well-presented include those relating to innovative technology implementation failure. Furthermore, they highlighted the importance of the risk associated with the introduction of new technology as an important area for future research. Figure 2.2 categorises the risks of relevance to the introduction of innovative construction plant and machinery. An informed decision relating to the feasibility of innovative plant and machinery deployment can only be taken after the identification and possible quantification of the associated economic, financial, managerial and

technical uncertainties. The following sub-sections describe the inherent uncertainties described within the existing literature.

2.4.1 Labour implications

There has been considerable debate concerning the role of human operatives in automated construction operations. There may be changes required in human capital (skills) which may be required to accommodate an innovation (Deiaco *et al* 1990). As experienced in manufacturing industries, the use of computer controlled equipment generally involves additional labour costs for programming, control and updating activities (Slaughter 1997). The deployment of robots will produce jobs for those who improve and innovate their design, as well as those who repair and maintain them (Richardson & Trowell 1994). As a consequence of the introduction of robotic equipment, Naoum (1994) speculated that there would be an increase in the amount of directly employed labour, while the need for casual labour would decrease. Subsequently, contractors overall labour flexibility would decrease. However, in line with modern plant management, innovative plant and machinery may be hired with operators, which would subsequently allow contractors to maintain their casual and flexible labour employment policies.

Automation and robotics will displace human operatives and their know-how, while such technology may simultaneously create pressure for a profound re-skilling (Cusack 1992). Chao and Kozlowski (1986) identified activities, which highlighted the division of labour between human operators and automated systems, these included surveillance (monitoring), intervention, maintenance, work inspection and synergy (the integration of human and robot actions within a production process).

Everett and Slocum (1994) concluded that human operatives continue to be more productive and cost effective than machines for the information-intensive construction site tasks. Furthermore, they commented that machines, which can perform one

physically intensive task, operated by a human who provides sensory information for the machine, are technologically and economically feasible today. This indicated that by distributing the physical and information components of automated construction work between man and machine might allow the benefits associated with construction automation and robotics deployment to be realised without reliance upon autonomous control systems.

Importantly, there is considerable value attributed to increased construction safety. Everett (1994) described the generic ergonomic overexertion injuries that are common to all construction and civil engineering operations. They were as follows:

- *repetitive exertions* – performing the same acts or motions repetitively;
- *static exertions* – maintaining the same body position or some part of the body throughout each work cycle for prolonged periods;
- *forceful exertions* – an exertion to overcome weight, resistance, or inertia of the body or a work object;
- *localised mechanical stress* – mechanical tissue stresses in the area of contact with external objects;
- *posture stresses* – positions of the body that require more effort than others or result in compression or stretching of tissues in or around joints, e.g. nerves or tendons;
- *low temperature* – contact of the hand with air or work objects below 20°C or exposure to low ambient temperatures that result in reduced peripheral circulation; and
- *vibration* – contact of the hands with vibrating objects, e.g. percussion air-tools.

In a study of the attributes of 85 existing construction automation and robotics technologies, Slaughter (1997) discovered that over half of the sample technologies (57%) involved human control through direct or tele-operated controls either singly or in combination with additional controls for process or navigation functions. Further to an evaluative international survey of the state-of-the-art development and employment of building robots, Warszawski and Navon (1998) reported that of the systems currently in use (24 in total) 45% were tele-operated, 42% required pre-programming and 13% were of the on-off variety. This indicates that despite the implementation of these systems, there remained a need for human control and supervision. Obayashi (1992) commented upon the conversion of construction sites from a human system dominated environment to a machine dominated environment, with subsequent accident reductions and overall increased safety. However, human involvement in the control and monitoring of man-machine systems may be required for the immediate future.

2.4.2 Financial uncertainties

Regarding cost estimation, Obayashi (1992) concluded that in order to provide standards, there is a need to accumulate and analyse performance data from the repeated experimental work execution of existing technologies. However, there are legal and practical barriers associated with firms who are each others competitors getting together and discussing issues, pooling resources and sharing information that is sensitive to their operations.

In evaluating the costs and benefits of information technology (IT) investment within the construction, Marsh and Flanagan (2000) used subjective data in the absence of reliable work-study data. Probabilistic methods were used to translate uncertainty into numerical probabilities by eliciting expert opinion regarding the upper and lower estimations of the associated costs and benefits. Finally, simulation of these

uncertainties allowed them to be varied simultaneously with a subsequent assessment of their inherent risk.

Perry and Hayes (1985) commented upon the presence of subjectivity in construction estimating and that an open recognition and analysis of risk and uncertainty will provide more realistic information on which to make decisions. Specifically, Warszawski (1999) suggested that much of the relevant data regarding a robot and its employment conditions may be unknown at the decision time and that such investment decisions must be based upon the analysis of the sensitivity of the effects with respect to all uncertain parameters. He then concluded that the number of sensitive parameters is extensive, with each of them varying considerably and often simultaneously, which deems any sensitivity analyses too large and meaningless. To counteract this he focuses upon several key parameters – the cost of labour saved, the cost of transfer and the rate of utilisation (hours per year)

In the absence of historical implementation cash flow data, estimates will be required for input costs whose true values are uncertain because they will be determined in the future (Lifson 1982). Objective probabilities are difficult to obtain from the construction industry, where each project is unique (Flanagan & Norman 1993). Specifically, the costs associated with operating and maintaining advanced construction technologies in adverse construction site conditions are not known (Slaughter 1997). If objective data is not available for determining probability distributions for inputs to a risk analysis model, then subjective data generated by experienced estimators is a suitable alternative (Akintoye & Macleod 1997; Chau 1995; Flanagan & Norman 1993). Probabilistic risk analysis is a powerful tool for investigating investment decisions, which rely upon predictions of future cash flows. Stochastic simulation, in the form of Monte Carlo simulation assumes that discrete investment appraisal input parameters are replaced with probability density functions. This recognises the dynamic project

environment and the possibility of various outcomes (Cooper 1975; Akintoye & Macleoad 1997).

The term 'risk analysis' originated with Hertz (1964). Hertz believed that the courage to act boldly in the face of apparent uncertainty can be greatly bolstered by the clarity of portrayal of the risks and possible rewards. The method aimed to aid executives in key capital investment decisions by furnishing them with a realistic measurement of embodied risk. Rather than predicting single estimates for inputs to investment decision models, Hertz proposed that probability distributions replace the discrete estimates and that these input distributions are sampled to generate an output 'risk profile' for the chosen performance criterion. Net present value calculations represent a single point on a continuous curve of possible combinations of future outcomes (Hertz 1983).

The essence of probabilistic risk analysis (PRA) is to provide decision makers with a greater awareness of the risks associated with a project's return and enable them to undertake more effective risk-return trade-off decisions (Ho & Pike 1991). The analysis results present a range of values in which the final outcome could lie (Thompson & Perry 1992). The resultant probability density functions are a powerful measure of project risk exposure (Raftery 1994). PRA reduces descriptive uncertainty, i.e. the absence of information about the identity of the elements of a problem structure, thereby enhancing decision confidence and increasing the probability of acceptance (Ho & Pike 1992).

Cash flow data may be subject to variability and uncertainty, due to unfamiliarity with the costs associated with automated construction technology. Probabilistic risk analysis will provide a means for including this uncertainty within a valuation framework. Risk measurement will provide those concerned with the decision to invest in construction automation with awareness of the risks associated with the investments return; an

insight into the most sensitive costs or savings to the overall profitability of the investment and, assistance in making a more effective investment decision.

2.4.3 Technical uncertainties

Technical uncertainties arise from the possibility of equipment failure, design failure, possible accidents or collisions and errors in estimations. Furthermore, the operational and maintenance requirements may generate uncertainty with regards to the level of training and skills required for the successful repair and maintenance of such technologies.

Warszawski (1999) commented upon the need for robots to be reliable in their ability to operate in a typical construction environment. He reported that with some existing technologies 15% to 20% of their operational time is spent on various 'troubleshooting' requirements. However, it is questionable whether such technologies should have undertaken more extensive off-site testing and evaluation prior to site deployment. Reliability is directly related to productivity, as without reliable machine operation it may prove to be impossible to achieve the specified and desired productivity rates.

Complementary changes that could be required to use a technology may include the overall design of the facility, and the modification of the material to be used in its construction (Slaughter 1997). Examples of such complementary changes include the provision of openings large enough to facilitate movement of equipment between floors and column spacing suitable for automated finishing technologies. Material modifications include dimensional changes, innovative connections or increased material tolerances.

The process by which new technology is introduced is not just a matter of replacing existing hardware but is conditioned by a number of factors relating to the generation,

use and co-ordination of knowledge (Deiaco *et al* 1990). The generation of new knowledge is fraught with uncertainty, and learning by using and doing is as important as formal R&D.

2.4.4 Managerial uncertainties

For a new technology to be introduced effectively it must not be introduced in a vacuum, therefore, the social system it will be part of must be taken into account (Statt 1994). The sources and causes of resistance to the introduction of automation and robotics were summarised by Navon *et al* (1992; 1993). The general categories of resistance were:

- fear of unknown changes or uncertainty;
- desire not to lose something of value;
- fear of personal inability to handle new requirements;
- inadequate understanding of need for the change;
- poor implementation efforts; and
- labour-management relations.

In order to reduce resistance, the following communication and education techniques may be implemented:

- training for operators and other involved personnel;
- resistance-reduction education for managers;
- feedback mechanisms/two-way communication;
- orientation programs, explaining the need for the new system;
- demonstrations, followed by discussions of the systems capabilities and limitations to reduce fear and anxiety; and

- meetings (both formal and informal).

The costs associated with these resistance reduction measures may be of importance to the financial appraisal of potential innovative technology investment opportunities. However, it is questionable whether there will be resistance as described above, with incremental evolutionary changes in the deployment of automation and robotics. Furthermore, with the involvement of plant-hire organisations, certain training and education requirements will be the responsibility of the machine owner and operator provider.

With the deployment of innovative technologies, there may be concern over their reliability and productivity. Prior to the manufacturing of automated plant and machinery, it must undertake extensive testing and evaluation. The reliability of a new machine may be questionable due to the 'burn-in' of components. However, these early failures may be covered by the manufacturer's warranty and the involved plant-hire firm may provide a temporary replacement. These issues are directly related to the uncertainty surrounding technical failure, and contingency plans must be prepared.

The quality improvements associated with automated construction technology may be reflected in material savings due to higher precision, and better performance of the finished product when compared to traditional techniques (Warszawski 1985; Kangari & Halpin 1989). Any improvements in the quality of a finished structure may be quantified in relation to the reduced snagging period and the direct cost of undertaking remedial work. The evaluation of any new technology must consider the possibility of quality improvements and these must be incorporated in any feasibility study.

2.5 Strategic valuation of construction automation investment opportunities

The future is uncertain and investment appraisal techniques that fail to recognise this will almost certainly lead to incorrect conclusions and erroneous recommendations (Brokfield 1995). Furthermore, for investment involving new high-risk business ventures it may be wise not to rely upon traditional discounted cash flow (DCF) approaches (Reimann 1990). Traditional DCF investment appraisal techniques alone, tend to systematically undervalue strategic investment opportunities (Kemna 1993; Smith & Nau 1995; Busby & Pitts 1998; Smith & McCardle 1999; Amram & Kulatilaka 1999a; Huchzermeier & Loch 2001; Copeland & Antikarov 2001). Net present value (NPV) analyses assume unchanging investment scenarios and do not incorporate potential investment flexibility options. NPV investment appraisal techniques do not capture and reward the value of managerial flexibility (Busby & Pitts 1997; Coy 1999). NPV analyses assume that management are passive in their attitude to potential investment projects and that future project value remains static in response to unexpected developments (Trigeorgis 1993). Furthermore, in competitive business, there will be occasions when a purely strategic decision is required (Wilkes & Samuels 1991).

Kaplan (1986) highlighted the intangible value of learning when considering the introduction of computer integrated manufacturing technologies. The manufacturing companies that invested in automatic and electronically controlled equipment in the mid-1970's were well positioned to exploit the micro-processor based revolution that developed during the early 1980's. Even if the expected project-based benefits of an innovation do not appear to off-set the initial costs, the act of innovating itself may provide strategic benefits and enhance the companies corporate image, reputation and competitive position (Kangari & Miyatake 1997; Hampson & Tatum 1997; Slaughter 1998, 2000).

The value derived from the use of construction automation and robotics technologies extends beyond the obvious tangible benefits. There is considerable strategic value associated with the decision to invest or implement such technologies. Existing appraisal methodologies do not incorporate this value. More appropriate appraisal methodologies are required to assess the true value of the investment and deployment opportunities available to contractors and plant-hire organisations.

2.6 Limitations of traditional appraisal techniques

Sangster (1993) conducted a survey of quantitative investment appraisal techniques in Scotland's largest companies. It was discovered that the payback period technique was the most popular method, then the internal rate of return (IRR) method, followed by net present value (NPV) and finally, the accounting rate of return (ARR) technique. In a survey of the top 100 UK construction contractors, Baker *et al* (1998) concluded that the investment appraisal techniques commonly used in the construction sector were expected monetary value, break-even analysis, scenario analysis and net present value.

The payback period is the time taken for future cash inflows to match their initial outlay. However, when using this technique, the time value of money is ignored. Furthermore, cash flows arising after the payback period is reached are ignored and the payback period that firms stipulate for assessing investments has little theoretical basis.

The IRR technique assumes that cash flows can be re-invested at the project's rate of return. This infers that the re-invested cash flows are compounded forward at the project's IRR, rather than the true cost of capital. The IRR method incorporates a bonus of the assumed benefits accruing from the re-investment of interim cash flows at rates of interest greater than the cost of capital (Pike & Neale 1999).

The application of excessive discount rates within NPV analyses technique is a potent force for investment short-termism and under investment (Wilkes & Samuels 1991; Drury & Tayles 1997). Furthermore, the NPV of an investment opportunity is calculated using estimates of tangible benefits only and places little emphasis upon difficult-to-quantify issues, such as quality enhancement or production flexibility (Shank 1996). NPV, alone, assumes that there is no flexibility in the investment appraisal process. The uncertainty of future cash flows is not modelled within NPV analyses. In reality, there are many possible future paths for cash flows over the economic life of an investment. These alternative scenarios are not incorporated within NPV analyses. The NPV decision is constrained to a “go or no go” investment decision (Copeland & Antikrov 2001). Finally, the ARR method takes no account of the size, economic life of the investment and the timing of cash flows over the economic life of the project.

A survey of UK investment appraisal practices discovered that when valuing advanced manufacturing technology, many UK organisations were risk averse and appraised projects conservatively by using excessively high discount rates (Drury & Tayles 1997). Furthermore, Adler (2000) asserted that DCF methods promoted a short-term decision horizon and that the use of excessively high discount rates greatly diminished the benefits of future year’s cash flows. From highlighting the above deficiencies in traditional investment appraisal techniques, the need to substitute construction automation and robotics investment appraisal with a more appropriate strategic valuation technique is emphasised.

2.7 Summary

This chapter has reviewed the existing literature relating to construction automation economics, investment risk and strategic valuation. Initially, the lack of clear and

unambiguous research describing existing capabilities and currently deployed technologies has highlighted the need to investigate the deployment status of construction automation and robotics. Specifically, there is a need to assess the post innovation improvements and the abandonment of inefficient technologies. Secondly, the existing generic valuation models for automated technologies were described with particular reference to the use of DCF methodologies. Thirdly, the uncertainties associated with construction automation and robotics technologies outlined in existing literature were identified. The use of probabilistic risk analysis to evaluate the inherent financial uncertainty was emphasised. Fourthly, the limitations of existing strategic valuation and appraisal methodologies were highlighted and, in particular, the inappropriate use of DCF techniques. Finally, the existing literature on the strategic valuation of construction automation investment opportunities were discussed.

This section summarises the identified drawbacks and omissions within the existing literature. In conclusion, it appears that from this review that research gaps in the subject of construction automation economics and strategic valuation methodologies occur in the following areas:

1. Investigative research is required to assess the current status of technological capabilities and their deployment status.
2. There appears to have been limited discussion regarding the role that plant hire organisations will assume in the deployment of construction automation and robotics.
3. The allocation of research and development, ownership, and operating expenses have been attributed to the end-users of automated construction technology. In practice, these costs will be fragmented amongst machine manufacturers, plant hire organisations and construction contractors.

Investment appraisal methodologies must attribute the appropriate costs to the appropriate organisations.

4. There appears to be a requirement for probabilistic risk analysis models using historical, where available, and subjective estimations of the costs and benefits associated with construction automation and robotics investment opportunities. Specifically, there is a need for greater understanding of the associated uncertainties and subsequent risk exposure.
5. The use of DCF investment appraisal techniques has presented only 'now or never' investment scenarios, which ignore investment flexibility and the intangible value associated with construction automation investment opportunities. Therefore, such investment opportunities require more appropriate appraisal methodologies, which incorporate flexibility options, investment dynamics and provide greater understanding of their strategic value.

It is these areas that the thesis aims to address, with the following chapters assessing current technology capabilities, investigating the Japanese contractors attitude, opinion and experiences with existing technologies and developing a generic risk evaluation methodology. Finally, developing real option pricing valuation models for the strategic valuation of construction automation investment.

Labour equivalent
man-hours

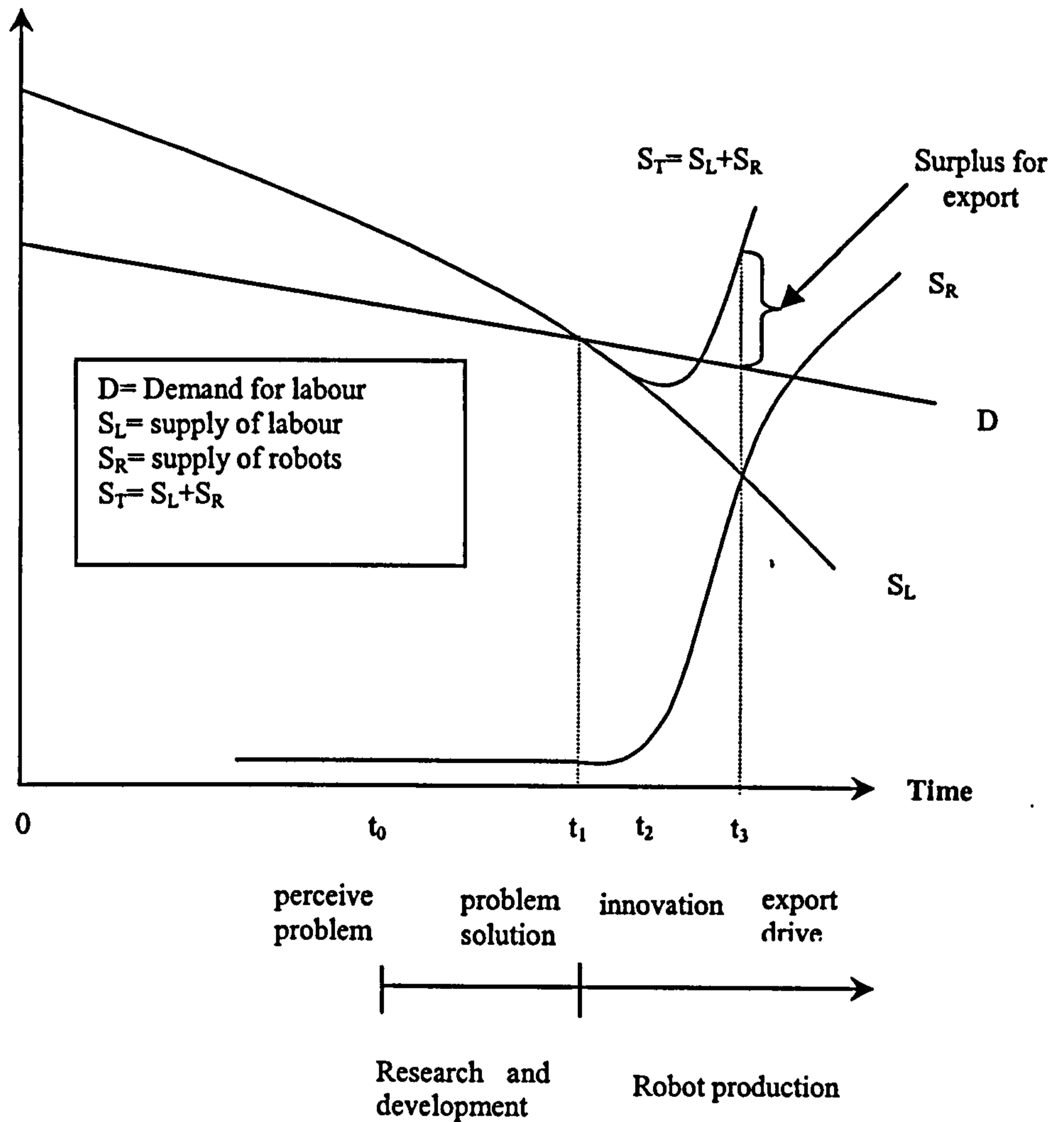


Figure 2.1: Supply and demand of Japanese construction automation
 Source: Bennett *et al* 1987

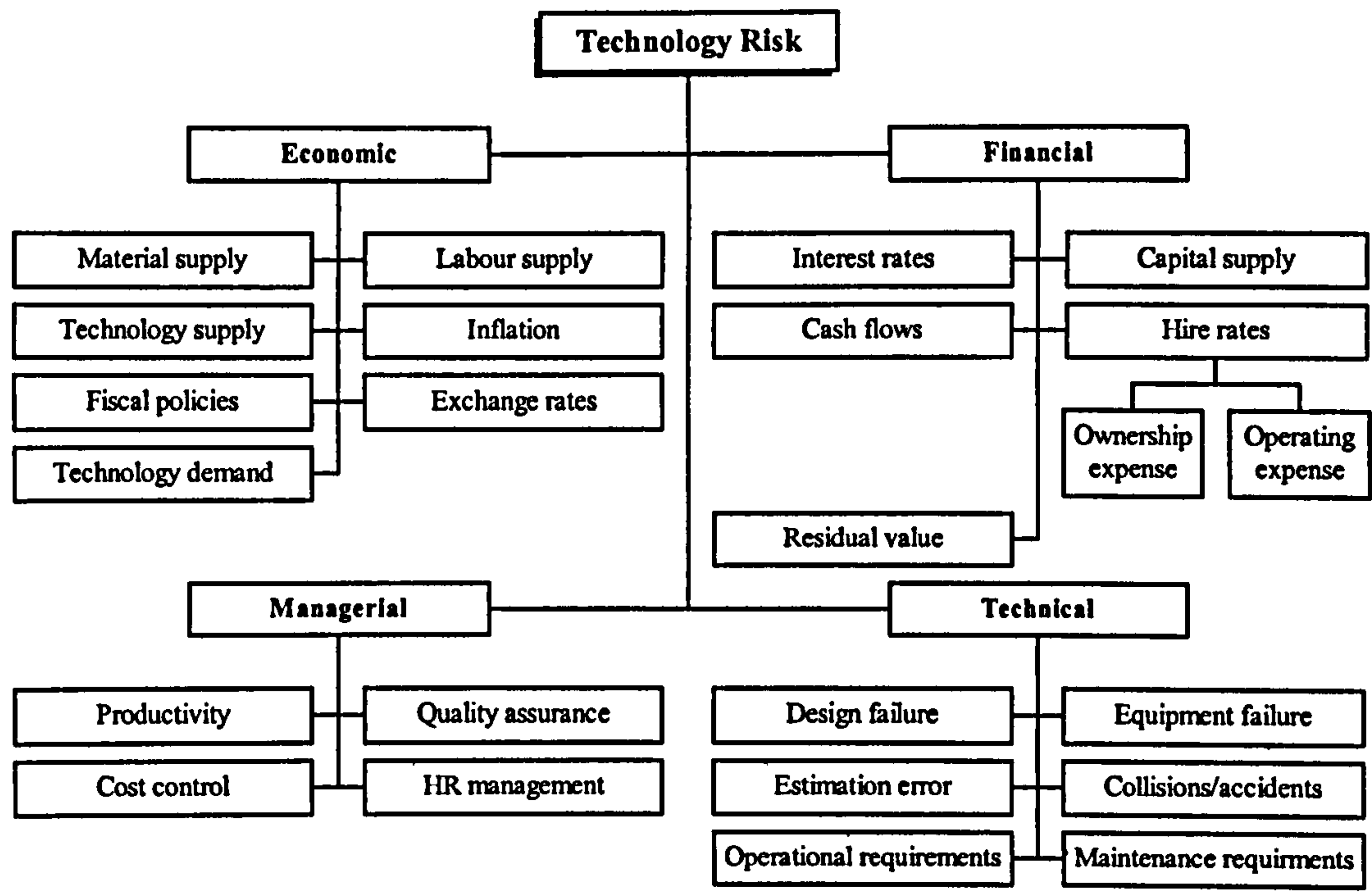


Figure 2.2: Categorisation of technology risk
 Source: adapted from Edwards & Bowen 1998

CHAPTER 3

THE STATE-OF-THE-ART TECHNOLOGY

3.1 Introduction

Automobile manufacturing has experienced rapid growth and development through the application of robots. Japanese construction managers expect a similar success story for automation and robotics in the construction industry that has occurred in the manufacturing industry (Everett & Saito 1996). However, there are fundamental differences between the fixed base manipulators used in automobile manufacturing and the systems that have been developed for application on construction projects. Peculiarities of the construction industry when compared to other sectors include the one-of-a-kind nature of operations, the requirement for on-site production and the temporary organisation of managerial, engineering and site staff (Koskela 1993).

This chapter introduces and discusses the methodological approaches adopted in examining the attitudes, opinions and experiences of Japanese general contractors in the research, development and application of automation and robotics. International capabilities are critically examined and future research directions are investigated. The analysis initially focuses upon evolutionary concepts. Finally, the analysis converges upon revolutionary systems, which are unlike any existing construction technology.

3.2 Definition of a construction robot

The first official definition of a Robot was presented in 1979 by the Robot Institute of America (RIA), and read as follows:

'...programmable, multifunctional manipulator designed to move material, parts, tools, or specialised devices through various programmed motions for the performance of a variety of tasks'.

The International Standard Organisation (ISO) has formulated the following definition with respect to robots and manipulators.

'A manipulating industrial robot is an automatically controlled, re-programmable, multi-purpose, manipulative machine with several degrees of freedom, which may be either fixed in place or mobile for use in industrial automation applications'.

The term "construction robot" is ambiguous and may be applied to the existing developments in the application of industrial robotics to international construction and civil engineering operations (Cobb 1998).

The International Association of Automation and Robotics in Construction (IAARC) defines a construction robot as a machine, which complies with the above basic requirements. Secondly, the machine must be suited to its purpose. A construction environment is fundamentally different to the comparatively well structured factory and the demands for mobility and robustness impact upon the design criteria for construction robots.

The fundamental difference between industrial manipulators and construction robots is outlined in Figure 3.1. Manufacturing robots are stationary and the product passes through

the manipulator zone of influence on an assembly line. On a construction project the final product is static, whilst the robot must be mobile and capable of navigating unstructured terrain. The technological requirements of a construction manipulator are more complex and sophisticated than that of the manufacturing industry. There is a need for additional sensors, a navigation system, a locomotive unit and a self-contained energy source. Figure 3.2 outlines the basic technology for automation and robotics in construction.

3.3 Selection of appropriate research strategy

This section discusses the overall research strategy employed for investigating the opinion, attitudes and experiences of Japanese general. The main aim of the research was to provide an in-depth understanding of the present circumstances of automation and robotics research, development and deployment within the Japanese construction industry.

In order to overcome language, business culture barriers and to facilitate a greater understanding of existing capabilities, there was a need to undertake in-depth interviews of Japanese construction executives, architects, civil/site engineers and research engineers concerning their experiences with automated construction technology. Furthermore, in order to understand the operational and technical requirements of existing technologies, there was a need to observe operational systems within laboratory and site conditions. As survey-based techniques are generally unable to answer “why” type questions, it was concluded that a survey based approach would be insufficient in understanding the pertinent issues relating to the research, development and application of automated technology within the Japanese construction industry. Therefore focus group discussions were adopted to allow a more in-depth study of the issues facing early adopters of automated construction technology within the Japanese construction industry.

3.3.1 Qualitative methods

Qualitative research techniques provide the means by which phenomena can be explored in detail without having to be fitted into artificial groups for the ease of analysis. As the terminology suggests, qualitative techniques examine the qualities of phenomena without specifically looking to statistical techniques. Thus a basic premise of this thesis is that the complexity and broad scope of the issues under examination could not have been adequately understood solely through quantitative analysis.

Table 3.1 summarises the main types of qualitative research techniques, together with their relative strengths and weaknesses. Focus group interviews were chosen as the most appropriate technique for eliciting information to satisfy the research objectives. These have strengths in being targeted, insightful, in-depth, interactive and capable of overcoming language barriers, allowing discussion on complex subjects and facilitate the efficient collection of data from groups. Three main shortcomings are identified with qualitative techniques, these being bias generated from poorly constructed questions, poor moderation, response reflexivity and open access to subjects and information.

Through the methodology adopted in this thesis, bias and reflexivity have been minimised through careful investigation and probing of focus group participants to ensure that answers given were a true reflection of reality and their attitudes. In addition, the fact that all focus group participants had received the question guide prior to being interviewed, provided stability in the qualitative aspects of the research. Access was highlighted in the methodological literature as potentially being a major hindrance, however, each focus group participant was contacted prior to the meeting to ensure that this problem was minimised.

3.3.2 Benefits and limitations of focus groups

In order to enhance the benefits of focus group research the researcher and moderator must be fully aware of the limitations and disadvantages of the qualitative focus group based research technique. The following section outlines the benefits and limitations associated with using focus groups as a method of collecting qualitative research data. Table 3.2 summarises the issues relating to the benefits and limitations of focus group based qualitative research.

The geographical location, and the language translation problems associated with conducting global mail surveys, hindered the collection of reliable data. Focus groups enable the accurate and speedy collection of emic data, i.e data in its natural and indigenous form. The opportunity for participants to respond in their own words would contribute towards the understanding of the complex technical issues being investigated within the research. The difficulties associated with language were more easily overcome with face-to-face interaction and, hence, the results obtained were more easily interpreted due to the moderator being able to request response clarification.

Merton (1987) and Morgan (1995; 1997; 1998a; 1998b) outline the obstacles that users must be familiar with before conducting focus group research. Morgan (1995) commented upon the desire to have smaller groups when dealing with experts or people in authority. When dealing with complex issues the experts may become irritated if they are not given enough time to be allowed to respond fully to the question posed. Hence, the focus groups were conducted with a maximum of eight participants and a minimum of two. The traditionally recommended size of a focus group has ranged from 6 to 12 participants (Krueger 1994). However, small focus groups, or mini-focus groups, with 4 to 6

participants are becoming increasingly popular because smaller groups are easier to recruit, host and are more comfortable for participants (*ibid*). Furthermore, smaller focus groups are preferable when the participants have a great deal of information to share about the topic of discussion. It is acknowledged that it may be inappropriate to generalise from the results of two-participant focus group, although the selected participants are specifically selected due to their expertise and their opinions generally represented those of the company.

Group *synergism* is an inherent component of Japanese business protocol. A Japanese businessman, rather than being an autonomous individual, is generally seen within the context of a company hierarchy. Within Japanese business protocol there is greater emphasis on society and the smooth functioning of the business group rather than individual rights. Group synergism may lead to participants providing answers, which are in-line with their colleague's responses. *Groupthink* is the tendency for nonconformists to suppress their disagreement in favour of maintaining consensus within the group. The problems associated with groupthink are of particular interest to this study. Recognised as an important difficulty, the problems associated with participant's opinions and responses being influenced by interaction may be included in the measurement process. Carey (1995) commented that a means to ameliorate this problem is to have group members write down answers to some or all of the guideline questions before the session begins. Through asking each group respondent to compile individual responses to the guideline questions prior to the focus group study, the problems associated with group synergism and groupthink were minimised. Participants were generally within similar bands of their company's hierarchical structure and therefore were not too concerned with proving their technical competence or knowledge of the subjects discussed.

Members of specific cultures are quite reserved and reluctant to discuss openly behaviours and issues that may lead to embarrassment or loss-of-face. For example, when asking questions regarding implementation failures, unprofitable ventures or accidents relating to the use of construction automation, Japanese executives may not readily provide information which may be seen to undermine the companies corporate image. Japanese group decision making may allow negative questions to be asked if responses can be given based upon the general consensus of the focus group participants. The executives and engineers may be more forthcoming in a face-to-face interview than with a mail-survey questionnaire. In coping with sensitive topics, a more prominent, stable and naturalistic approach is beneficial in that it creates a greater degree of trust between the focus group respondents and the moderator.

3.4 Focus group design and implementation

Semi-structured focus group interviews were conducted with relevant executives, managers, research engineers and technicians within purposively selected Japanese general construction contractors and selected public research institutes. In combination, this original source of information, together with the published literature, provide the means by which the research objectives were developed and satisfied.

The nature of the research hypotheses raised required qualitative methods to answer the “why” classification questions that quantitative techniques alone could not adequately address. This resulted in the collection of information concerning the attitudes, opinions and experiences of the leading Japanese general contractors employees’ being based upon a series of in-depth interviews. The focus group interviews were less rigidly structured, and provided opportunity for open discussion concerning the research topic.

3.4.1 Focus group design

The identification of companies for interviewing was founded upon previous demonstration of the practical deployment of construction automation and robotics within the Japanese construction industry outlined within existing literature. Focus group participants were purposefully selected using *critical case* sampling (Patton 1990). Critical cases are those that are of particular importance in the overall research objectives. The focus of the data collection was upon understanding what is happening in these selected critical cases.

In order to generate valuable and relevant data, specific individuals were identified reflecting their particular qualities and their relevance to the topic of the investigation. The qualities of the individuals identified as relevant to the research include:

- currently employed by Japanese general contractor or government body in either project operations or in a research environment;
- appropriate seniority, i.e. a broad understanding of the organisation and operations of the firm; and
- previous experience with, and currently involved, in the research and development of construction automation and robotics (i.e., authored research publications – *Automation in Construction* or *ISARC* 1990 to 2000).

The advantage of *purposive* sampling is that it allows the researcher to home in on people or events, which there are good grounds for believing will be critical for the research (Denscombe 1998). The participants were selected on the basis of specific characteristics, building a sample of sufficient size and having the desired traits (Black 1999). The *snowballing* technique was also used to locate appropriate individuals by asking

participants, who had agreed to be involved in the research, the name and contact details of others who may also fit the sampling requirements (Oppenheim 1992).

The examination of critical cases, purposive and snowballing techniques are of particular importance where resources are limited and it is imperative that the focus group studies yield the most information and have the greatest impact upon the development of knowledge. However, by adopting these techniques it is difficult to determine exactly how the sample represents the population of concern.

This method of identifying companies to participate in the focus group studies, was self-selecting, since it was likely that those organisations with an interest in construction automation and robotics would be more likely to want to discuss their particular set of circumstances and the issues facing them and their organisation.

Given the detailed nature of each of the focus group interviews as well as the resource constraints, particularly those of time and finance, of interviewing companies based throughout Japan, companies with corporate head quarters and research facilities within the Tokyo area were identified and formally approached. Further to receiving positive responses from a selection of organisations a realistically achievable sample of eight general contractors, the Ministry of Construction and the Ministry of International Trade and Industry Mechanical Engineering Laboratory were selected.

The purpose of the focus group interviews was to gain a detailed understanding of the research issues through specific case studies of individual companies. The intention was that the individual case studies would combine to facilitate in-depth analysis of the status of

construction automation and robotics research, development and deployment within the Japanese construction industry. The examination of a selection of case studies does not permit broad generalisations across the Japanese construction sector, however, logical generalisations may be made from the weight of evidence produced in the study of the selected critical cases. Furthermore, focus groups were undertaken with leading government departments, which incorporated issues relating to public investment in Japanese construction automation and robotics research.

In order that there was as much consistency as possible, a *schedule guide* was constructed and used as a prompt for the moderation of each of the focus group interviews. The partially structured nature of the focus group discussions provided scope for the exploration of particular issues that were identified during the discussions, though generally the same issues were covered in each focus group discussion. This ensured that all the issues of pertinence to the research were raised with each individual group. To have solely used the questions within the *schedule guide* would have counteracted the benefits of using the focus group discussion methodology. The semi-structured nature of the interviews was utilised to provide a far greater depth of understanding of the issues facing that particular company and its present experiences with construction automation and robotics technology. The pre-prepared *schedule guide* was posted to each focus group participant prior to the meeting. This allowed the participants time to examine the translation and discuss the research questions. Furthermore, if any additional material of relevance would be required in the discussions, the participants were provided with sufficient time to obtain it.

The questions included reflected the specific elements of the research relating to:

- construction automation research and development expenditure;
- the perceived value of tangible and intangible benefits;
- the testing and evaluation of prototype technologies;
- the realised efficiencies relating to productivity, labour costs and operational safety;
- adjustments to organisational and managerial structures;
- the use of existing technologies on construction projects;
- the operation and maintenance requirements of existing technologies;
- the training and education of operatives;
- the exportation of developed technologies; and
- strategic construction automation research objectives.

The majority of the focus groups were undertaken in private research institutes with the remainder taking place at corporate headquarters, public research facilities or active construction projects.. The majority of focus group participants were either senior managers or research engineers.

3.4.2 Implementation of focus groups

The focus group interviews were conducted between September 2000 and October 2000. The focus group interviews were funded by the Royal Society of Edinburgh international travel scholarship (J M Lessells Scholarship Trust, 2000). Due to time and financial restrictions and the geographical location of the companies being interviewed, considerable difficulty was experienced in arranging the focus group discussions. It was unfortunately impossible to arrange to visit every construction contractor within the Tokyo area. As

interviews are highly labour intensive and time-consuming, only a limited number were undertaken. Furthermore, having limited financial resources and the high cost of living in central Tokyo limited the tenure of the focus group research period. Associated costs included:

- basic Japanese language lessons;
- travel expenses for moderator;
- subsistence expenses;
- office supplies, duplication and postage; and
- gifts for focus group participants.

A summary of the companies and organisations interviewed together with the number of participants and the location of the focus group discussion is presented in Table 3.3. The focus group sessions were undertaken on location in order to observe the research facilities of the group being studied. Furthermore, Table 3.4 summarises the designation of the focus group participants involved in the research study.

The purpose and objectives of the focus group meetings were explained to the participants via: (1) posting the provisional question schedule; and (2) informal e-mail correspondence prior to the actual interview taking place. Further to conducting the focus group discussions, the group participants were invited for a meal. This promoted additional conversation and communication within the group. During this period the moderator continued to listen for relevant comments concerning the research topic. Within this relaxed and informal environment, the participants offered beneficial comments or suggestions to the study.

Interaction between the moderator and the respondents allowed additional issues to be raised by the focus group participants. Supplementary issues were raised by the participants, which contributed greatly to the general understanding of the research topic. Rather than the participants providing discrete responses, the moderator was able to probe for further information and explore interconnected subjects with ease.

During the focus group discussions, it was discovered that the first three groups provided a considerable amount of new information, but by the third or fourth session the quantity of new information discovered decreased. However, there was specific value attached to the comparison of the research and development strategies of the corporate organisations interviewed.

3.4.3 Method of analysis of the focus groups

The focus group discussions were principally designed to collate qualitative information to specifically add depth to the research. The purpose and nature of qualitative techniques were discussed in Section 3.3.1, along with the advantages of obtaining information in less formal and rigid manner. The analysis of the qualitative data from the focus group discussions was designed to provide detailed understanding of the attitudes, opinions and experiences of Japanese executives and research engineers with automated construction technology. Furthermore, the qualitative data were used to enrich the results by using individual company case studies to highlight trends that, whilst not facilitating generalisation to the Japanese construction industry, were of interest in revealing a more detailed knowledge of the existing status of construction automation research, development and deployment.

Each focus group discussion was recorded through note-taking during the discussion itself, then pertinent issues were summarised in report form. This method was successfully implemented during the first focus group discussion and was found to be satisfactory throughout the remaining focus group discussions. It allowed comprehensive notes to be constructed, without the issues of confidentiality and general reluctance to provide in-depth and industrially sensitive information, which is often found with audio recorded meetings (Taylor 1984).

Report writing requires a balance between the direct quotation of the participants and the summarisation of their discussions. Too many quotations give the report a chaotic structure and too much summarisation is dry and deprives the reader of indirect contact with the responses of the participants. Data interpretation comes down to a question of which topics should receive the most emphasis in the eventual report. Three basic factors: (1) how many groups mentioned the topic, (2) how many people in each group mentioned the topic, and (3) how much energy and enthusiasm the topic generated among the participants. Focus groups are no different from other forms of qualitative data, there is a perpetual tension between the richness of the data and the remoteness of the reader from the source data.

In order to summarise the responses of each focus group, response data was analysed using a 'grid' system that systematically summarises what each group said in response to each question. Computer assisted content analysis, through the simplistic counting and sorting of words, may lead to the loss of the context in which words occur. Although the coding of context units may overcome this difficulty, there is the inherent difficulty generated from the Japanese respondents conducting the focus group in English.

The focus group discussion reports facilitated detailed analysis of group participant responses to specific research questions and provided a means of highlighting any additional information regarding the individuals and companies experiences with construction automation and robotics technology. The reports were used to identify common attitudes, opinions and experiences between the group participants and their companies. The reports also provided identification of opinions and experiences that may be generalised to the Japanese construction industry as a whole. The analysis of the focus group discussions also included samples of quantitative data, for example in determining the proportion of general research and development expenditure, which is specifically used for the development of construction automation and robotics technology.

3.5 Analysis of focus group results

The previous sections have considered the methodological issues surrounding the design, implementation and analysis of the focus group discussions. The results of the focus group discussions are used to provide an in-depth analysis of the current status of Japanese construction automation research, development and deployment incorporating the qualitative aspects of the research. The following sections provide an overview of the results of the focus group studies that were conducted.

3.5.1 Overview of focus group discussions

This section summarises the key outcomes of the focus group discussions and the information gained from the group participants. The focus group reports provide a comprehensive summary of the information obtained from each focus group in report form. The reports act as a reference to establish the key issues relating to the companies and

organisation involved, their existing experiences with construction automation and their ongoing research and strategic objectives.

Group participants provided additional information in the form of corporate brochures and promotional videos, which assisted understanding of the present status of their construction automation and robotics experiences. All of this information was incorporated in the results of the focus group discussions and provided supplementary information for additional questioning.

The research questions hypotheses and operational definitions are summarised in Table 3.5. Based upon the methodology used, the response grid shown in Table 3.6, 3.7 and 3.8 summarises the main characteristics of the group participants responses to the questions posed in the question schedule guide. Each research question and hypotheses is analysed in turn under general categories. Supplementary information, not originally intended for investigation, was provided by group participants further to additional questions developing throughout the scheduled meetings. This information is incorporated where appropriate. This section has provided an overview of the information gathered from the focus group studies.

3.5.2 Participant companies research investment and strategies

This section is concerned with the two hypotheses that aim to establish a greater understanding of construction automation research and development currently being undertaken by Japanese general construction contractors.

Hypothesis One Japanese contractors continue to employ a high percentage of mechanical and electrical engineers, which conduct in-house automation and robotics research and development.

Shimizu Corporation reported that they have reduced their research staff due to overall reductions in research and development made necessary by the economic recession, reduced annual profit and, therefore, reduced R&D expenditure. There was a similar trend described by the remaining focus group participants. This was due to the streamlining of research and development operations in order to reduce total expenditure whilst the economic climate recovered. The Takanaka Corporation commented that the current economic climate is not conducive to the further development of technologically sophisticated and prohibitively expensive automated construction technology.

Hypothesis Two Japanese contractors continue to contribute substantial investment towards the research and development of construction automation and robotics.

Despite the economic recession within Japan, the Big-Six general construction contractors continue to contribute substantial investment into to construction research and development. However, the scale of this investment has reduced significantly over the last five years (see Table 3.9). In conjunction with the general decline of R&D investment, there have been significant reductions in expenditure on the research, development and deployment of construction automation and robotics technologies. The Taisei Corporation reported that they have reduced their total R&D expenditure from ¥15.6 billion in 1994 to ¥8.38 billion in 2000 (see Table 3.10). In conjunction with this, there was a significant

decline in construction automation and robotics R&D expenditure. In 1994, ¥0.34 billion was allocated to their construction mechatronics R&D programme. However, by 2000 the figure was reduced to ¥0.06 billion. The reduction in construction automation R&D expenditure was reduced from 2.2% of the total R&D budget to 0.8% of the total by 2000.

Specific R&D expenditure information was deemed commercially sensitive and, therefore, was not provided by all participating organisations. However, general information regarding total R&D is available in annual reports and the participating contractors were agreeable in their company's decisions to reduce their construction automation R&D investment intensity whilst the present economic situation is rectified.

3.5.3 Participant attitudes regarding construction automation drivers

This section is concerned with the hypotheses that aims to examine the extent to which the participating Japanese general construction contractors value the tangible and intangible benefits of construction automation as drivers for their research and development activities.

Hypothesis Three Japanese contractors place greater emphasis upon the intangible benefits of construction automation and are more concerned with strategic, rather than, short term advantages and benefits.

The Tokyu Corporation research engineers highlighted the success of the board erection manipulator with respect to the provision of a stable mobile staging platform and the manipulator providing easier handling of construction materials and assisting in fine positioning of these components. The importance of reductions in strenuous work

involving ceiling/wall board erection exemplified the importance attached to improved work ergonomics during such operations. Furthermore, the focus group participants commented that the development of tele-operated and fully automated construction machinery is important for the safe and efficient development of subterranean structures. For example, the development of a tele-operated excavation system was initiated in order to reduce the exposure of human operatives/miners to the dangerous working conditions associated with the excavation of deep shafts and foundations.

The Obayashi Corporation commented that the pertinent issues relating to the development of automated construction technology were primarily operational safety followed by overall cost reductions. Site safety took precedence over construction cost reductions.

Dr Sueoka (Taisei Corp.) commented that despite the limitations of the existing prototype technologies, invaluable learning experiences have been realised and that future use of such technologies could be undertaken with ease.

Mr Hoshino (Takanaka Corp.) described how, at present, clients require low cost and subsequently deem automated construction technology uneconomical. However, increasing labour costs and the difficulties associated with Japanese demographics may justify the use of more expensive construction process technologies.

Dr Nishita (Maeda Corp.) in describing the operations of an semi-automatic column field welding system, commented that the man-machine system does not reduce the number of human operatives required, but greatly reduces human exposure to the hazardous conditions created during welding operations.

The Shimizu and Maeda Corporation commented that many of the research and development projects involving the construction of prototype single-task systems were to enhance the corporate image of the firm by using technological capability as a marketing tool. Therefore, greater emphasis was placed upon the research and development of prototype technologies rather than whether they were actually deployed on operational construction projects.

The tangible benefits identified by the focus group participants include:

- lower cost to clients;
- production efficiency/quality/accuracy; and
- labour reductions.

The tangible benefits identified by the focus group participants include:

- increased operative safety;
- improved work ergonomics;
- operational learning; and
- marketing tool emphasising technological prowess.

The focus group responses seem to validate the assumption that Japanese general contractor's are primarily concerned with operative safety and work ergonomics

improvements to be gained from implementing automation and robotics. However, overall cost reduction appears to be a secondary concern. Importantly, a selection of the focus group participants highlighted the value of the learning experiences realised with the research, development and application of prototype technologies.

3.5.4 Participating organisation procedures for testing, evaluation and implementation of construction mechatronics

This section is concerned with the hypothesis that aims to investigate the procedures that the participating Japanese contractors utilise in the research, development, manufacturing and implementation of construction automation and robotics technologies.

Hypothesis Four Prototype automated technology is extensively tested within laboratory conditions prior to trial on-site implementation projects.

In general, suitable construction tasks are suggested by the contractors and, in collaboration with plant and machinery manufacturers, prototype automated systems are developed and their performance evaluated within laboratory testing facilities followed by trial demonstrations on operational construction projects. Importantly, only minor difficulties are experienced on site with new systems as all prototype technology is tested and evaluated within structured environments that simulate project conditions in order to resolve any operating and technical complications. Mr Hoshino (Takanaka Corp.) commented that only minor operational difficulties occur on site and that these are generally easy to deal with. Machine manufacturers involved in previous construction automation research and development projects include Komatsu, Caterpillar, Kawasaki, Honda and Mitsubishi.

An exception to this standard research and development procedure was the Kumagai-Gumi construction machinery division, which undertake the design, manufacturing, testing and evaluation of their automated construction technologies in-house.

All focus group participants commented upon the requirement for a JIRA operating licence for new automated construction plant and machinery. This enables the operational safety of each machine to be evaluated and monitored prior to on-site application.

The focus group responses validate the general assumption that new automated construction plant and machinery is tested and evaluated prior to use on operational construction projects. This may be of considerable importance when contractors, unfamiliar with such technologies (e.g. UK contractors), are implementing them in conjunction with Japanese contractors collaboration. Importantly, operating procedures and production rates are practically guaranteed prior to the use of Japanese systems on operational construction projects.

3.5.5 Participant attitudes regarding perceived construction efficiencies

This section is concerned with the hypothesis that aims to investigate the extent to which Japanese contractors have realised the efficiencies of production, quality, labour reductions and safety that were perceived during earlier research and development of construction automation and robotics technology conducted from the 1980's.

Hypothesis Five Automation and robotics is providing Japanese contractors with the perceived efficiencies relating to construction productivity, labour costs and increased operational safety.

Among the focus group participants, there was a general consensus that the recent economic conditions within Japan are stifling the widespread use of automated construction process technologies. Dr Nishita (Maeda Corp.) commented that there was abundant investment capital during the early research and development programmes initiated during more prosperous economic conditions. Furthermore, there was considerable pressure to undertake R&D activities due to competitive pressures in the domestic construction sector. Low labour and material costs are causing the more advanced automated construction systems cost ineffective.

The single-task systems developed from the early 1980's have proven to require extremely high rates of utilisation to recur their research and development costs. Dr Maeda (Shimizu Corp.) commented that despite high rates of utilisation, certain fully automated systems are not providing sufficient returns to justify their further deployment. Dr Inoue (Obayashi Corp.) commented that although automated construction technologies provided great prestige for the company, they are seldom used because of the high costs associated with their manufacturing and operation. Man-machine and tele-operated construction process technologies are providing increased production productivity and quality for certain operations, e.g. concrete distribution, concrete finishing, automatic material conveyance, earth moving, subterranean excavation and generic light-weight material manipulators. However, owing to the need for human operators to control and monitor the operations of existing systems, labour reductions appear to be minimal.

In general, utilising automated construction technology generally inflates the overall cost of a construction project. According to Mr Takaba (Kumagai-Gumi Co. Ltd.), there are two general exceptions to this assumption. These are as follows:

1. the labour costs, which were reduced as a consequence of the use of the automated system, exceed the total cost associated with the automated system; and
2. the high performance of an automated system contributes to an overall reduction in the total construction schedule and results in a cost saving for the overall project.

Recent applications of integrated automated construction systems (IACS), i.e. ABCS, SMART, MCCS, T-Up and Roof Push-up, have proven that these systems must be more extensively utilised in order to provide sufficient cost savings to compensate the developers for the considerable R&D expenditure incurred throughout their development. The cost effectiveness of these systems is dependent upon the number of storeys within the structure and their rate of utilisation. Further to the application of IACS's, automated procedures have been scaled down and recent research efforts have centred upon the use of high-rise construction systems which rely more upon human operation and monitoring rather than automated control systems, e.g. Big-C and *NewSMART*. These more simplistic high-rise construction systems are proving to be a more realistic alternative to the technologically complex IACS systems.

From the comments made by the focus group participants it is evident that autonomous single-task technologies are not providing the labour cost reduction benefits initially perceived during the research and development programmes initiated in the 1980's. However, man-machine and tele-operated systems are providing valuable advantages with regards to increased productivity and operative safety. Furthermore, the use of simplified

high-rise construction systems (e.g. Big-C and *NewSMART*) may provide future tangible benefits for the contractors who have developed these systems once the Japanese economy experiences growth.

3.5.6 Participating organisations adjustment to structural designs and construction processes

This section is concerned with the hypothesis that aims to examine the design and construction process adaptations that Japanese construction contractors have undertaken to assist the introduction of automation and robotics within their operations. Furthermore, information concerning the associated organisational and managerial changes required was sought.

Hypothesis Six Japanese construction projects are being re-engineered to accommodate automation and robotics.

To facilitate the use of ABCS system the Obayashi Corporation have developed the Obayashi Strategic Integrated Construction System (O-SICS). The O-SICS system aims to integrate design and construction site process information to facilitate the sharing of process engineering information between architects, design and construction engineers via an internet based electronic data interchange database. The database incorporates the ABCS and Big-C system within a total production management system. This computer network controls material manufacturing, shipment and movement from storage facilities to their final installation locations. Bar codes are attached to all building components at the prefabrication plant and information regarding the type of element, dimensions and erection

location are ascribed. The system facilitates real time monitoring of construction progress and machine status.

In order to assist large scale construction and civil engineering operations involving plant and machinery, the MoC PWRI are developing a project based network for the interchange of information concerning machine status, productivity, survey data, machine maintenance requirements and production quality control. The system has been designed to assist unmanned machine operation in the monitoring of a large number of machine from one central control database.

The Shimizu Corporation have established a computer integrated construction (CIC) system, which operates in conjunction with the SMART and *NewSMART* high-rise construction systems. Computer control systems are applied in the operation and control of the construction manipulators as well as the overall management of the construction process. The construction site, project office and head office computer systems are connected via a local area network. Project office systems monitor lifting and material conveyance, compile information concerning record drawings, temporary works schedules, machine status and quality control. Work in progress is monitored via cameras and site engineers record progress using hand-held portable computers.

With the use of IACS's structures are designed with greater pre-fabrication and complete service modules are designed to facilitate rapid erection at the construction site. Taisei Corporation research engineers commented that structures are designed with the deployment of the T-Up system in mind. Design and construction engineering are closely

integrated to allow detailed planning of all construction activities to be undertaken prior to construction commencement.

Regarding the use of man-machine and tele-operated construction plant, the focus group participants were adamant that such technology did not require the adaptation of organisation and managerial structures. They stated that such technologies were similar to traditional plant and machinery with regards to their operational and maintenance requirements. However, project managers required additional training in understanding the operation and interpretation of the information management systems.

3.5.7 Participating organisations practical experiences with automation and robotics

This section is concerned with the hypothesis that examines the practical deployment of automation and robotics within the participating organisations construction projects. Details of construction and civil engineering projects, which have utilised automated technology, were sought. Furthermore, focus group participants were probed for specific reasons for the successfulness of their deployment.

Hypothesis Seven Construction automation and robotics is extensively utilised throughout domestic Japanese construction projects.

A selection of single-task tele-operated systems have proven to be valuable in conducting concrete placement and finishing operations. The deployment of tele-operated earth moving plant has provided substantial productivity efficiencies, but their wide spread application is questionable. Furthermore, material manipulation systems for interior

finishing operations appear to be broadly utilised and are proving to be invaluable tools for repetitive interior construction.

Integrated automated construction systems have been successfully deployed on a broad range of high-rise construction projects. However, the use of the more heavily automated systems (e.g. ABCS, SMART, MCCS, T-Up) has proven to be less economical than the more simplistic Big-C and *NewSMART* systems. Although, these more simplistic systems have been used on a small number of operational construction projects. It must be remembered that these systems are revolutionary concepts that will inevitably require extensive utilisation in order to streamline their operation and provide substantial benefits over and above traditional construction procedures.

From the focus group participants' responses, it became obvious that automated construction technology is not as extensively utilised as existing literature and corporate brochures lead readers to believe. Man-machine systems appear to be providing valuable improvements in labour productivity. However, the deployment of autonomous construction automation is proving to be too technologically perplexing. The rationalisation of integrated automated construction systems is providing more economical automated construction and sufficiently controlled operational environments for the deployment of automation and robotics.

3.5.8 Participants experiences with construction automation operation and maintenance

This section is concerned with the hypotheses that examine the operating and maintenance requirements of existing construction automation technologies in conjunction with the

training and education of operators and maintenance technicians. Specific details regarding the operation, repair and maintenance requirements of existing technologies were sought. Furthermore, the skills required by operators and maintenance technicians were investigated in conjunction with details of construction contractors and manufacturers involvement.

Hypothesis Eight Existing construction automation and robotics technologies, currently employed on Japanese projects, require highly skilled operators and maintenance personnel.

Hypothesis Nine Contractors are educating and training the next generation of construction operatives to facilitate the future deployment of automation and robotics.

Owing to collaboration with machine manufacturers, selected focus group participants commented that operators and maintenance engineers are trained as part of the machine development programme. Alternatively, operators and maintenance technicians are trained in-house within the private research facilities with their training being continuously updated as new machines and control systems are developed.

Importantly, the Obayashi Corporation research engineers commented that they use a sub-contracted labour force when using the ABCS or Big-C systems. These specialist sub-contractors are experienced in the control and maintenance of the systems and are used on all projects. The operatives are trained by the research engineers responsible for the design and development of the systems. The use of the same sub-contracted operatives provides specialist knowledge and expertise that may not be available from alternative contractors.

The research engineers interviewed highlighted that the automated construction technology requires maintenance engineers with maintenance skills similar to those required for automated manufacturing systems. However, owing to the scale of size of certain systems, maintenance and repairs may prove to be more expensive and time consuming.

3.5.9 Participant organisations exportation strategies

This section is concerned with the hypothesis that examines the technology exportation strategies of the participating organisations. Details concerning the hire or lease of existing technologies, possible collaboration with machine manufacturers and issues concerning technical support were sought. Furthermore, reasons for organisations not marketing their technology for sale overseas were investigated.

Hypothesis Ten Japanese contractors are aiming to hire and lease specialist construction systems to proliferate automated construction technology deployment within international construction markets.

The Obayashi Corporation provides information regarding the hire of their Big-C system for use by a construction contractor in the construction of high-rise structure in Singapore. The system was shipped by sea and assembled on site. Obayashi Corporation research engineers provided technical support and assistance during the operation of the system. The project was completed within schedule and to the specification.

The Tokyu Corporation commented that the exportation of automated construction plant and machinery would require communication routes via subsidiary offices based in the country of deployment. Importantly, trained operatives and maintenance engineers would be required to support any deployment out with Japan.

During a discussion regarding the practical application of the Maeda Corporation's column field welding robot, Dr Nishita commented that stemming from the high capital cost of the equipment and a need to secure high rates of utilisation, a hire/leasing system would be required to provide economical operation. Furthermore, international hiring/leasing operations may be undertaken if there is sufficient demand for such technologies.

Importantly, the Taisei Corporation commented that they are not concerned with the manufacturing of automated construction technology. Therefore, the marketing of such technology overseas would be undertaken by the machine manufacturers.

A selection of the construction contractors interviewed appear to research and develop automated construction technologies purely for their companies competitive strategies. Both the Shimizu Corporation and Kumagai-Gumi commented that the systems they have developed are to enhance the competitiveness of the firm and, therefore, will be used on contracts within which they are directly involved. However, if these organisations market their construction and civil engineer services abroad, they may incorporate their advanced construction technologies (depending upon shipping costs).

3.5.10 Participants attitudes regarding future research directions

This section is concerned with the hypothesis that elicits opinion regarding the future construction automation and robotics research objectives for the participating organisations.

Hypothesis Eleven Computer integrated construction and integrated construction automation systems are pertinent to the strategic objectives of Japanese contractor's construction automation research and development.

There was considerable discussion regarding the further development of automated high-rise construction systems. Importantly, network and communication systems will assist in the future development of integrated automated construction systems. The greater integration of design and construction to facilitate the deployment of automation and robotics is also a prime objective.

Remotely operated construction plant and machinery will become an invaluable tool for the development of future sub-terrestrial construction projects. Furthermore, the general deployment of man-machine technologies will greatly improve site safety and provide increased labour productivity and quality.

However, there was considerable scepticism regarding the short-term future of construction automation and robotics research and development. The Takanaka Corporation commented that they have postponed their construction mechatronics research and development programmes until Japan's economic climate is more conducive to the development of such sophisticated and expensive technology.

3.5.11 Summary of hypotheses evaluation

Table 3.11 summarises the evaluation of the focus group research hypotheses developed within this Chapter. It is evident that there are considerable contrast between the reported success of construction automation and robotics technology (i.e. journal papers, conference papers and corporate brochures) and the actual status of machine deployment within the

domestic Japanese construction industry. The present economic climate within Japan has not been conducive to the research, development and deployment of construction automation and robotics technology. However, there was general consensus regarding the strategic value of the learning and operating experiences gained in the undertaking of construction automation and robotics research and development programmes.

3.5.12 Discussion of focus group findings

This research has used qualitative research techniques. It has focused upon gaining a more detailed understanding of the complex issues surrounding the research, development and practical deployment of automation and robotics on construction projects. The research has been able to gain evidence as a means of developing an understanding of the key issues, without claiming to be wholly representative of the Japanese construction industry

In a way that quantitative research could not, the focus group studies provided an in-depth insight into the opinions, views and experiences of the participating Japanese general contractors, machine manufacturers and public construction organisations. The conducted qualitative research facilitated the appreciation and understanding of the basic principles underlying the actions of the Japanese construction contractors interviewed. Drawing upon their previous experiences and ongoing R&D with construction mechatronics technology, the focus group participants were able to identify which technologies have proven to be successful, the requirements of their construction industry and future directions for construction mechatronics research.

One interesting theme that reoccurred throughout the separate focus groups, was the need for a specialist plant hire organisation to manage the deployment of construction

mechatronics technology. The participants commented that for such expensive and technologically sophisticated technology to be economically viable, it must be extensively utilised. Subsequently, the involvement of plant hire organisations in the proliferation of such technology is imperative.

A related theme that emerged from the focus group sessions was the general reduction in R&D expenditure and, specifically, a reduction in construction mechatronics R&D. The group participants affirmed the strategic importance of construction mechatronics technology and indicated that they continue to give serious consideration to the future implementation of more advanced technologies. However, they stressed that in order to provide more cost-effective construction, the cost of using mechatronics must be reduced by simplifying the construction process technologies and using greater pre-fabrication.

Many participants described their close relationships with machine manufacturers and specialist sub-contractors, which facilitated the testing and evaluation of systems prior to site implementation. However, others expressed their desire to conduct private research in order to benefit the operations of their firm exclusively.

For investigating the current status of construction mechatronics technology within the Japanese construction industry, using focus group methodology to explore industrial attitudes, opinions and experiences proved to be a useful for several reasons. Firstly, the participants appeared comfortable in each session and they freely shared details of their experiences with their organisation. The response of one participant often brought to mind a specific experience of another group participant, which lead to greater information being shared and discussed. The *face validity* of these findings is high, due to the findings

coming directly from industry professionals and not from secondary sources. However, caution has been exercised in assessing the reasoning for the obtained opinions, views and information concerning experiences with construction mechatronics technology.

Through understanding and adhering to Japanese business protocol, trust was built as was an environment where participants felt comfortable to discuss issues, which were sensitive to the strategic operations of their organisation. This generated greater potential for valid responses than might have been achieved using a mail survey questionnaire. Secondly, the focus groups were judged successful because they resulted in the participants sharing the particular information that they intended to elicit: the status of construction automation and robotics research, development and deployment. This information was valuable in assessing the current status of automation and robotics within the Japanese construction industry.

Thirdly, the focus groups bestowed the information necessary for the development of an in-depth analysis of the existing industry demand for construction mechatronics technology, the systems currently in operation and the future directions for the R&D of construction mechatronics technology. By identifying the above, the research gained information on technology, which may potentially be introduced within the UK construction and civil engineering industry.

Fourthly, group participants were provided the opportunity to voice their personal opinion, irrespective of their companies' policy. This was an important outcome of the focus group process, as opinions were often suggested on the basis of what a participant thought of research and development conducted out with their firm. The focus group participants were

able to qualify their responses or identify important contingencies associated with their answers. Therefore, the responses have ecological validity, which is not found in traditional survey research.

There were considerable resource constraints due to the limited time and funding for the research. Specifically, a Japanese-English interpreter would have provided more fluid interaction and may have assisted in eliciting more information. Alternatively, the moderator could have been more skilled in the Japanese language. Of particular influence was the time constraints placed upon the research due to the substantial subsistence costs associated with living within Tokyo. Subsequently, the tenure of the research was limited and more time would have facilitated meeting more contractors, visiting more construction projects and technical research facilities.

Regarding the authenticity, accuracy and honesty of the information provided, the moderator was initially aware of the extent to which Japanese construction contractors are using automation and robotics as a marketing tool. Subsequently, any information, which appeared to be too impressive in comparison to the achievements of competitors, was probed for further authentication.

Following the conventions and procedures of software programmes detrimentally effects the intuitive art of analysis in qualitative research. They leave little scope for interpretative leaps and inspirational flashes of enlightenment and reduce analysis to a mechanical chore (Denscombe 1998). Furthermore, computer analysis provides a tendency to focus upon the literal or superficial content of the transcript text and removes the data from its emic context.

Overall, the focus group methodology adopted served as a valuable tool for eliciting in-depth emic data concerning the opinion, attitudes and experiences of Japanese construction industry professionals and academicians regarding the research, development and implementation of construction mechatronics technology. The focus group method was time consuming and labour intensive, the data collected and presented in this thesis has highlighted important issues, which may be of value to those wishing to develop implementation programmes. While these findings are important to academics in directing future research, an examination of the Japanese contractor's experiences may be of value to UK contractors and plant-hire organisations considering diversifying into mechatronics technology. Importantly, the *predictive validity* of the research relates to the extent to which the results of this research may be confirmed by future behaviour. Furthermore, it must be remembered that the attitudes, views and opinions measured within the present study may be subject to change over time.

3.6 Categorization of automated construction technology

Over the past two decades, Japanese general contractors and machine manufacturers have gained an extensive knowledge base and developed a varied selection of practical solutions to common construction activities. Figure 3.3 displays the categories of existing automated construction systems and the number of these systems, which have been developed within Japan.

Having analysed the basic activities in building construction, Warszawski and Sangrey (1985) categorised prototype construction robots into four sub-divisions and provided detailed performance specifications for each category. Based upon these performance specifications, the four categories were:

- *Assembly robots* - an anthropomorphic manipulator with a reach of 20-25m and a payload of 1-3 tonne. The arm may have 3-4 DF (degrees of freedom) with an additional 2-3 DF at the wrist for the orientation and precise positioning of elements. The robot would be used for hauling and positioning large building components, e.g. steel members, pre-cast concrete members and semi-assembled formwork.
- *General purpose robots* - to be used for general purpose building interior operations, e.g. painting, grouting, nailing and bolting.
- *Floor finishing robots* - to be used for horizontal finishing operations, e.g. trowelling, glue spreading and brushing, which involve large floor areas. The robot will consist of an effector attached to a mobile platform where the end-effector is effected through the movement of the carriage.
- *Exterior wall robots* - used for finishing activities, such as painting, plastering, weather-jointing and finish inspection of large areas on the exterior of buildings. The system may be tele-operated or pre-programmed for the desired task and performance area.

Warsawski and Sangrey (*ibid*) concluded that the deployment of automation within the construction sector required development of existing hardware, mainly in the area of locomotion and sensing, together with the adaptation of the building process to facilitate the use of robots.

In a discussion on the role of automation and robotics in next generation Japanese construction, Ueno (1994) summarised the existing trends in construction automation research and development. These existing trends are as follows:

- Single task systems:
 - a) low cost tele-operated systems, and
 - b) intelligent robots
- Construction automation (Integrated Construction Automation Systems)

In an international survey to evaluate the state-of-the-art research, development and deployment of building robots, Warszawski and Navon (1998) reported that many of the respondents specified that their robots had some pre-programming options, although in many cases they were tele-operated. The number of respondents who reported the deployment of intelligent (i.e., robots that include pre-programming capabilities and sensors) was almost negligible. The sensors employed were ultrasonic, tactile, tension meters, lasers, optical, infrared, position measurement, pressure transducers and inclinometers. The breakdown of control systems reported is presented in Figure 3.4.

In a review of existing Japanese automated construction technology, Cousineau and Miura (1998) presented a hierarchical breakdown of current capabilities. Figure 3.5 illustrates the five main categories of single-task systems and their subsequent sub-categories.

It is evident that their control functions and their level of automation differentiate single task construction robots. Furthermore, the integration of these single task systems is the main objective of re-engineering the construction process using integrated construction

automation systems. Construction automation research and development has generated divergent approaches to automating construction and civil engineering activities and ongoing research appear to be adding further stratification as more complex construction and civil engineering operations are successfully automated.

3.6.1 Enhanced traditional plant & machinery

Enhancing traditional construction plant and machinery, using sensors and data processing capabilities will facilitate improved operator feedback, refined control, increased safety, productivity and quality. Advances in sensors, actuators and control systems technology is creating opportunities for the increased automation of existing construction plant and machinery. Typical automated features of semi-automatic construction plant include: auto-slope, excavation depth control, bucket hold, automatic grading, ditch finishing and high/low limit settings (Gann 1995). The addition of process and navigation controls takes advantage of current capabilities of mechanisation in the industry while reducing the number of degrees over which the human operators have to exert control (Slaughter 1997).

Existing methods of advanced control for construction equipment include (Greer *et al.* 1997):

- single degree of freedom joysticks;
- multiple degree of freedom joysticks;
- operating and safety constraints;
- teach/Learn capability;
- resolved motion with internal and external sensors;
- spatially correspondent controllers;

- tele-operation;
- graphical programming and control; and
- autonomous control;

As control systems become more complex they become more difficult to implement and the operator is increasingly removed from the control loop. New control systems for construction plant are developing at a rapid pace. Figure 3.6 shows the traditional excavator, which has been adapted to incorporate remotely controlled actuators and cameras to provide the remote operator with advanced control systems are improving quality and safety whilst reducing labour costs. Figure 3.7 depicts the tele-operated control and monitoring system for the unmanned operation of the excavator. This technique may be applied to a broad range of construction and civil engineering plant and machinery.

Since 1993, the Japanese Ministry of Construction has utilised unmanned construction machinery to remove volcanic ashes and deposits generated from within the vicinity of erupted volcanoes (Nagao 1997). Machinery used included bulldozers, backhoe excavators and transportation of spoil with dump trucks. The machines were operated from a distance of 2 km by means of radio controls, GPS and stereoscopic images. Project data, such as real time positioning and progress monitoring, assisted in the efficient management of earthmoving operations and quality control.

Tele-operated construction machinery is particularly suited to mining, quarrying and civil engineering projects requiring large earthworks. The technology frees machine operators from hazardous working environments and may protect them from possible machinery

related accidents. Furthermore, the productivity and efficiency of the machine operators may be more readily monitored.

3.6.2 Single and multi-task systems

This section examines the single and multi-task systems, which have been developed to conduct construction operations previously undertaken by human operatives. Automated and tele-operated systems have been developed to undertake a broad range of construction related activities. A succinct and quantitative review of the specification features, application requirements, level of on-site deployment, economic, technical and operational viability is discussed for the currently available range of single task systems.

Concrete distribution & finishing

The *in-situ* distribution of wet concrete is traditionally a labour intensive operation. The process of transporting, feeding and distribution must be continuous and within a specified time period. The development of tele-operated articulated concrete distribution arms improves quality and safety whilst greatly reducing the number of labourers required. Figure 3.8 depicts a horizontal concrete distributor with the ability to avoid obstacles and decrease the time required to place the wet concrete. The use of distributive cantilever arms with radio control consoles allow the boom pump to be manipulated whilst the machine operator is located in close proximity to the shuttering and the concrete operatives. Figure 3.9 shows a Putzmeister hand-held control panel for a tele-operated concrete boom pump. This system is commercially available and has proven to be successful in increasing the overall efficiency of concrete pouring operations.

The successful implementation of fully autonomous control systems poses significant obstacles for construction robot manufacturers. Figure 3.10 depicts the Kote (trowel)-King system developed by the Kajima Corporation (Japan). The system could navigate over a pre-programmed course within a pre-determined area and adjust its course as required. Further to on-site trials, the machine proved to be too complex and financially non-viable when compared to traditional finishing techniques. Further to the development of less sophisticated tele-operated versions at the present, the use of such technology does not appear to be economically viable.

The “Robocon” system (see Figure 3.11) was used throughout the construction of the Kajima Corporation Maruzenshoû project. The project consisted of a four-storey distribution and warehouse facility. A specialist concrete sub-contractor, Takahashi Construction Systems Inc., employed the radio-controlled system to finish the concrete floors throughout the structure. The machine provided a more consistent and durable finish compared to traditional trowelling techniques and reduced the overall cost of the finishing procedure.

Structural steel welding systems

The use of automated manipulators within steel manufacturing facilities is widespread, however, the application of on-site welding robots has presented research engineers with new challenges. The site-welding robot must be suitable for the harsh and dynamic conditions, which prevail on construction projects. Existing solutions to automating site-welding procedures require manual monitoring and inspection. However, to increase the productivity of the machines and the operators, more than one machine is operated at any one time.

Nisita *et al* (2000) presented details of the development of a prototype column-field-welding robot. The system consists of a pair of welding robot units, control units, teaching boxes, water coolers, wire-feeders and guide rails (see Figure 3.12). The robot guide rails are fixed to brackets, which are attached to each column during fabrication. Power cables, control cables and gas hoses are then connected to the equipment. The type and thickness of the column are input into the control teach box. The welding groove shape and dimensions are measured by a wire touch sensor system prior to welding commencing. Following weld completion, the system is manually disassembled and transferred to the next column location and re-assembled.

In order to improve the economic feasibility of site welding robots, greater automation is required. At present, man-machine welding systems appear to be viable solutions to partially automating site-welding operations. However, fully autonomous site welding requires further development of the associated control technologies. Automated welding systems are discussed within the context of integrated automated construction systems in following sub-sections.

Material manipulation

The faster transportation and manipulation of construction materials contributes significantly to productivity. High performance rugged mechanical arms with characteristics suited to full robotic control are practically and economically realisable with current technology (O'Brien 1992). The assembly of steel and pre-cast concrete elements constitutes the core of construction operations and, therefore, the highest benefits can be obtained from automating these activities (Warszawski & Snagrey 1985).

Material manipulators have been developed as practical solutions to placing oversized heavy components within the construction environment. Figure 3.13 depicts an interior finishing materials handling manipulator. The system facilitates the erection of light steelwork, ceilings and positioning plaster boards. Furthermore, the machine eliminates the need for temporary staging during the erection period. The ability to greatly increase productivity and site safety, without unnecessary technical complexity, justifies the deployment of these lightweight material manipulation systems.

The positioning of composite steel flooring deck plates requires construction operatives to work at height. Working at height increases the possibility of accidents and objects falling from height and striking operatives working at ground level. In order to increase the efficiency of composite deck plate erection and increase site safety, Kumagai-Gumi Co Ltd. have developed the deck plate positioning system (see Figure 3.14). Having positioned a pile of deck plates using a crane, the deck positioning system can automatically, via a remote control console, collect each plate and position it to facilitate immediate fixing. The system has been successfully deployed on a selection of high-rise construction projects and has provided increased productivity and operational safety (Watanabe *et al* 1999).

Figure 3.15 shows a standard Kuka KR210 heavy-duty manipulator. The standard Kuka manipulator is being used as a constituent of a heavy-duty mobile construction manipulator. Further to attaching the manipulator to a tracked locomotive base unit, the system may be applied to a wide variety of construction material manipulation tasks. This concept represents ongoing research being undertaken by the Institute of Control Engineering of Machine Tools and Manufacturing Units (ISW) within the University of Stuttgart.

O'Brien (1992) disputed that existing robotic manipulators used within the manufacturing industries are not sufficiently large or generally appropriate for general application on construction projects. A new range of precise action robotic tools, with large reach, high load capacity and designed specifically to suit the rugged site conditions within which these systems will operate. The preliminary performance parameters included:

- 1 tonne lift capacity;
- 2-5mm positioning accuracy under full load;
- zero backlash under full load;
- 10m, or more, lifting radius;
- 6 degrees of freedom;
- real-time computer control; and
- low cost (i.e., purchase, maintenance, repairs and operation).

The manipulator arm would be mounted upon rails or a tracked crawler base which provided 360° rotation. Simple trials were conducted using the prototype manipulator equipped with tools such as grippers, drills, jaw cutters and circular saws as end-effectors. Safety features of the manipulator include full load holding capabilities in the event of possible failure of the primary power system.

Zied *et al* (2000) and Seward *et al* (2001) describe the development of a prototype heavy tool-manipulator robot for the construction industry (Starlifter[®]). Key applications for the system include diamond core drilling, anchoring and concrete cutting. These procedures traditionally require human operators and present significant operational health hazards, i.e. hand-arm vibration from prolonged use of percussive vibration tools. Figure 3.16 shows an

operational prototype of the Starlifter manipulator system. The system has the following mechanical properties:

- six degree-of-freedom;
- load carrying capacity of 200 kg at any orientation of the first joint;
- all joints can be simultaneously locked in any selected position with power and control shut down to provide a stable platform for the deployment of heavy duty tooling systems;
- automatic tool changing facility;
- arterial supplies to tooling adapter, i.e. 200 bar hydraulics, electrical power, 2 video channels and a maximum of 10 tool-function controls; and
- tele-operated control with programmable capabilities.

The nature of construction materials requires considerable mechanical effort in their positioning and placement on construction projects. The ability for material manipulation systems to greatly increase the productivity of construction site operatives, more accurately position structural components and provide greater operational safety will assist the construction industry in providing more efficient structural erection and interior finishing operations. Further research is required in the development and application of material manipulation systems for deployment as generic construction site tools capable of transporting, orientating and positioning structural components.

Finishing systems

Interior and exterior finishing robots for construction operations are being developed to work in conjunction with innovative materials design to provide increased productivity and finished quality during the final stages of building construction projects. As selection of the various mechatronic systems, which have been developed to date, are presented in the following sub-sections.

Interior

Prototype interior-finishing robots have been developed to conduct the various tasks involved in the completion of residential, commercial and industrial buildings. These works may include the erection of partitions, painting, plastering of walls and ceilings, jointing of prefabricated components, attachment of conduits and tiling (Warszawski & Navon 1991). Multi-purpose interior finishing systems present an economically viable alternative to the various single-task automated construction systems, which have been previously developed. Operating from mobile base units in combination with tele-operation and pre-programmed operation, these systems can successfully utilise an array of alternative end-effectors to successfully accomplish interior finishing tasks. This sub-section presents a review of the various prototype multi-task interior finishing systems, which have been developed to date.

Mobile Robotics ÅB has developed a prototype autonomous plastering robot (see Figure 3.17). The system was developed in conjunction with a Swedish plaster manufacturer and selected industrial robot manufacturers. The machine can locate window apertures, door openings, apply plaster with greater productivity, provide increased quality and generates less waste than its human counterpart. However, further to on-site trials, the system

received little attention from the Swedish construction sector. The reason for the disinterest was due the recession within the Swedish construction sector and in particular the housing sectors (the industry in which the system would be extensively implemented).

The machine reduced the quantity of material wastage, therefore, the plaster manufacturing company would inevitably lose revenue in terms of the amount of plaster it sold if the machine was more widely utilised. Subsequently, due to the housing industry recession and disinterest from the sponsors, the system has been shelved and has not been manufactured on a commercial basis. However, the system may be utilised to apply paint with slight adjustment to the nozzle and pumping systems. Therefore, future applications for this system may be successfully developed when industry demand is sufficient to justify the research and development costs.

The Technion Autonomous Multipurpose Interior Robot (TAMIR), is an experimental pre-prototype interior finishing robot whose size and configuration are similar to those desired for the operational model. The robot has been adapted from a S-700 manipulator manufactured by General Motors and Funac (see Figure 3.18). The manipulator has 6 DoF, a nominal reach of 1.62m, a maximum payload capacity of 300 N. The S-700 manipulator has been mounted upon a three-wheeled mobile carriage (see Figure 3.19). The manipulator can be guided using a remote control console, however, future research aims to equip the system with sensory devices to enable autonomous site navigation. In a study of the economic feasibility of the TAMIR system, Warszawski and Rosenfeld (1994) concluded that the employment of a multi-purpose robot for interior finishing work has considerable potential for construction site productivity improvements.

Developed from the SSR-1 prototype fireproofing application system, the Shimizu Corporation have developed and successfully applied the SSR-3 steel fireproofing application system (see Figure 3.20). The SSR-3 system includes an off-line teaching capability, which facilitates the programming of the robot from a remote computer. The system also continues spraying whilst the base locomotive unit travels along the length of the structural member. Operatives were relieved from the hazardous and laborious activities associated with the application of fire protection material. However, the system did not provide the envisaged labour reductions due to the new operational requirements of the machine. As with other fully autonomous prototype systems, the reduction of automated procedures and increased man-machine capabilities greatly enhanced the operational effectiveness of the machine (Cousineau & Miura 1998).

The concept of a generic construction robot capable of undertaking a broad range of construction site activities appears to be a practical means of ensuring the economic justification of an interior construction robot. Cyclical demand, varying specifications and high capital costs within the construction sector, requires flexible strategies similar to the manufacturing sectors (Bock *et al* 2000). Robot orientated construction requires standardised planning, production and assembly systems. The above considerations lead to the development of the modular robot system shown in Figure 3.21. The modular system is based upon a transportation module, which can interface with interchangeable specific technology process modules (Feldmann & Koch 1998). An image processing system mounted upon the transportation module assists navigation via a manually applied chalk line.

The machine is capable of following the chalk line and detecting the pre-marked points of operation. Inter-site travel and changing from one line to another is controlled manually using a joystick. Applications include setting tiles, anchor bolts, false ceiling supports, cleaning and the supply of heavy materials. The components for the transportation unit and the ceiling bolt installation module have been developed and a prototype system has been constructed (see Figure 3.22).

In order to facilitate the automated construction of interior finishes, the Waseda University construction robot research project (WASCOR IV) has proposed the amalgamation of pre-fabricated construction and automated on-site erection. The research examined the development of a building construction method suited to automated erection, the design of a hardware system for conducting interior finishing tasks and the development of an information management system (Hanada *et al* 1996). The project proposed a building system, which consisted of pre-fabricated units for constructing beams, columns, walls, ceilings and floors. Quick acting joints were developed to facilitate unit erection using the material-manipulator.

Exterior

Traditionally, painters work from either scaffolding or gondolas hung from the roof of a structure. Occupational hazards include working at high elevations and exposure to solvent fumes. In order to combat these, and similar occupational hazards, exterior paint application systems have been developed for the completion of tasks including painting, plaster application, surface inspection, joint sealing and tile placement and positioning (Warszawski 1999).

According to Cousineau and Miura (1998), the common features of paint application robots include:

- spray paint application systems;
- operation remotely, by either manual or automatic sequence control; and
- spray mist containment system to prevent unwanted spread of paint.

The Tokyu Corporation have developed automated paint application system, which can be used reproduce either multi-coloured images or apply monochrome paint to structural elevations and steel silos. Figure 3.23 shows the main components of the paint application robot and its control mechanisms. The paint application robot is hung from a gondola positioned on the roof of the structure. Lateral movements are minimised by restraining the guide cables by fixing them to a support bracket, which travels along a guide rail as painting progresses. The machine can be pre-programmed to apply intricate patterns, which can then be automatically applied to the structure. Figure 3.24 shows the system painting a basic five-colour design on an elevation of the Tokyu Corporation Technical Research Institute. Figure 3.25 shows the system being used to paint a replica section of a steel silo structure. Automated painting of this type of structure may facilitate unmanned painting and eliminate the need for operatives to work at height. Furthermore, multiple machines may be operated and monitored by a single operator. Therefore, increasing the rate of which these structures are painted. The system has a remote control console, which can be used to manually operate the system. The system is currently only a prototype, but successful site demonstrations have been undertaken which indicate greatly improved paint application productivity. Furthermore, the system eliminates the need for human operatives to work at height and be exposed to solvent-based paint fumes.

Multi-storey structures with homogeneous façades are suitable for the application of automated cleaning systems. In the development of an automatic cleaning system, Schmucker *et al* (1998) proposed that their cleaning robot provided a number of benefits when compared to traditional manual cleaning operations. These included:

- reduced cleaning cycle times;
- low operating costs;
- cleaning difficult-to-access areas;
- flexible cleaning cycles (cleaning of especially dirty façade areas or cleaning on demand);
- consistent value and aesthetic appeal through regular cleaning; and
- ecologically friendly cleaning.

The machine was designed specifically to suit the dimensions and spatial constraints of the structure. The cleaning unit is hung from a gondola, from which water and electricity are passed to the cleaning unit via an umbilical cord. All drive mechanisms, electronic elements, water and cable drums are mounted on the robot. The inclusion of automated cleaning facilities within the planning and design of multi-storey structures will expand considerably in order to alleviate the health and safety difficulties associated with high elevation cleaning operations.

Within Japan, steel radio antenna masts are painted in order to provide protection to the structural steel. The antenna coatings lose their properties with age and often flake off, which may result in corrosion of the structural steel. Traditionally, human operatives climb the antenna and apply the paint using hand-held spray. Due to the inherent health and

safety implications with this type of work, the Taisei Corporation have developed an automated antenna tower painting robot. The ATPR-01 device is raised and lowered using a mechanical winch and paint is supplied to the spray application device from a pump on the ground. The paint-tank, paint pump, compressor, winch, paint hose reel and the central control unit are located on the ground in close proximity to the antenna base. The system was developed in collaboration with Nippon Housou Kyoukai (NHK), a Japanese antenna manufacturer.

Masonry construction

In order to reduce the physical strain placed upon bricklaying operatives, increase productivity and enhance the finished quality of site masonry, the development of automated brick laying systems has been actively pursued by construction automation and robotics research engineers. The following sub-section provides a detailed account of the prototype systems, which have been developed for performing automated on-site masonry construction.

Aiming to improve the competitiveness of bricklaying operations, the Lohja Corporation was the leading partner in the EUREKA programme: a Europe-wide network for industrial R&D. The project involved the development of a mechanised brick laying system for deployment on building sites (Vähä 1992). The system consisted of a track-mounted brick laying platform, hoisting equipment, conveyors and auxiliary equipment. The platform provided a transportation system for the equipment and a temporary scaffolding structure for manual inspection requirements. A prototype system was developed and on-site trials demonstrated that the system could provide increased productivity and improved work ergonomics.

Pritschow *et al* (1996; 1998) presented a prototype masonry robot based upon a commercially available demolition robot (BROKK BM180). The BRONCO system provided a practical and cost effective solution to automated bricklaying (see Figure 3.26). The system automatically manoeuvres using reflectors and a laser positioning system to determine its exact position. The system can determine the pallet position, automatically collect bricks from a pre-positioned pallet, apply a thin-bed mortar and automatically position bricks within the required tolerances. Although the machine can perform a selection of associated tasks autonomously, the system requires human input for defect detection the completion of complex tasks. Figure 3.27 outlines the geometric relationships, by means of a co-ordinate system, between the construction materials and the machine.

The economy of prototype automated masonry construction systems has been questionable due to the utilisation of low wage level human construction operatives. Training expenditure and the high development costs associated with current attempts to automate the masonry construction process are deeming the economic application of automated systems impossible. The BRONCO system has been abandoned as it was deemed too complex and prohibitively expensive for practical implementation. The system required highly skilled operators, hence, the system did not have practical applications within the German house building sector.

Ground engineering systems

Many geotechnical operations require work within confined operational environments. Operatives are exposed to hazardous working conditions, such as possible ground water ingress, shield failure, falling objects or toxic gases. The application of tele-operated or

autonomous excavation systems presents a viable solution to the problems posed by ground engineering projects.

Figure 3.28 depicts the Tokyu Corporation tele-operated excavation system. The tracked machine has a drum cutter for excavating soft rock and a small back-actor with bucket. Utilising a vacuum tube or a loading chute, the machine facilitates the swift removal of spoil. The machine has been successfully employed in the construction of tunnels, vertical shafts and large diameter piles.

Within the Koto ward of Tokyo (Japan), the Kumagai Corporation employed a triple faced tunnel boring machine (TBM) in the construction of the north-east extension of the Hanzomon underground railway line. The construction of Kiyosumi station and the associated storage track is bored with two lateral cutting faces forward of a central oscillating face (see Figure 3.29).

The tunnel section is composed of fourteen pre-cast concrete segments, which are positioned using a series of assembly manipulators. Automated procedures includes segment supply, segment gripping, precise positioning, and bolt tightening. The system greatly reduces labour requirements and increases safety during the erection process. Assembly accuracy is ensured through reducing the deviation of positioned segments and standardisation of bolt torque's.

The Giken GRB pile placement system consists of a material conveyance system (pile runner), a crane clamped to the previously installed piles, an engine unit and the silent hydraulic pile installation machine (see Figure 3.30). The system can be used to install U,

Z, Zero, tubular and H steel sheet piles. Furthermore, the system can also be used to install pre-cast concrete piles. The system hydraulically installs the piles silently without excess vibrations using the reaction force principle. Pile conveyance, orientation and final installation is executed using a range of specialist machinery, which can automatically travel along the previously installed piles in the direction of installation. Pile orientation and installation procedures are controlled via a hand held radio control console. The entire system can be operated using a single trained operator. The system requires no temporary staging facilities and utilises the pile wall as a platform for all required work. The system is available in a range of various capacities and, with the smaller systems, is particularly suited to urban work environments, which have inherent space restrictions (see Figure 3.31). The GRB system has the potential to minimise the problems associated with excess noise and vibration when conducting piling operations in urban areas (Wako & Iizuka 2000).

With greater use of subterranean structures, there will be substantial demand for construction systems, which eliminate human operatives exposure to the hazardous conditions associated with mining and deep excavations. Furthermore, implementing automated excavation systems may provide opportunities for increased productivity and quality.

Demolition systems

Since the 1970's, BROKK ÅB has been developing, manufacturing and marketing a range of radio-controlled demolition machines (see Figure 3.32). The Brokk demolition robot is the company's only product line. The range machines has developed and now comprises a complete range of varying capacities with a complimentary range of attachments. The BROKK systems success is due to the versatility of the machines. Available attachments

include hydraulic breakers, crushers, scabblers, grapples and buckets. These attachments provide the user with a machine capable of assisting all aspects of demolition and construction related operations. These systems are predominately utilised within steel mills, nuclear power stations and demolition projects. However, this type of machine may prove to be an invaluable tool for general construction site activities.

3.7 Off-line programming and simulation

The development of construction robots is an extremely expensive process. The development of computer simulation software capable of simulating automated construction technology may facilitate the development of prototype technology without cumbersome research and development expenditure. Considerable amounts of time and money may be saved in construction robot development through using simulation to decrease the need for refining prototype systems (Jansson 1994). Simulation provides feedback of a robot's interaction with its operational environment. Access and collision problems may be resolved prior to site implementation. Furthermore, simulation provides useful information about the capability of the robot to conduct a construction task (Seward *et al* 2001).

Off-line programming and simulation facilitates the preliminary design of robot applications and provides specific information regarding component geometry and the movement patterns during the machine operating cycles (Warszawski 1999). Manipulator movements are simulated using a graphical interface, where the operational effectiveness of the machine can be evaluated without having to test the actual automated system. Simulation provides immediate feedback of the machine interaction with its operational

environment. Therefore, potential access and collision problems can be resolved prior to site deployment.

Off-line programming allows an automated system to be programmed in advance, therefore, saving time due to the reduction in the need for programming the real system. Furthermore, having the programme on disk means that if the operational configuration of the system requires adaptation, the system can be quickly re-programmed with the previously constructed off-line programmes. The ability to simulate the construction of prototype systems and examine their operational effectiveness, without incurring the expense of actually construction the machine, presents significant opportunities for the investigation of automated systems for construction and civil engineering operations.

Jansson (1994) and Seward *et al* (2001) highlighted the need for off-line simulation results in determining the economic feasibility of construction robots. Through developing a detailed plan of the actual task to be undertaken by the robot system, productivity rates, safety procedures and preliminary cost estimates could be evaluated. It must be noted that when using simulation to design and assess the feasibility of construction robots, environmental effects are not considered. For example, the effects of friction, wind-loading, operator error and lateral vibrations (Seward *et al* 2001). Off-line programming may be used to plan, schedule and cost construction tasks executed using an automated system. The procedure is useful in process design, safety, procedure preparation and economic feasibility analyses.

3.8 Industrialized pre-fabricated construction

The application of automation within well-defined and structured environments has proven to be extremely successful within the manufacturing sectors. Greater mechanisation during off-site prefabrication combined with automated construction procedures may lead to higher quality and improved productivity. Within an automated pre-fabrication plant, the building elements are constructed using automated technology similar to existing manufacturing facilities. Rather than applying automated machines to the dynamic construction environment, they remain static and the materials are worked upon using a traditional assembly line procedure. Automated pre-fabrication of construction components may include the preparation of moulds, the preparation and placement of reinforcement, mixing and placing of concrete, vibration of concrete, curing, stripping and de-moulding (Warszawski 1999).

Off-site and field factory production systems are dependent upon flexible mechatronic systems and easily reconfigured production facilities. These leaner design and construction processes focus on value for money, improved productivity, maintainability and sustainability. Industrialised building systems generate savings in construction cost and in construction time together with a reduction in defects on completion, enabling industry to be more competitive overall.

3.9 Computer Integrated Construction

Considering the current trends in information technology, many large construction companies are finding integrated construction to be an attractive strategic option in meeting increased competition (Miyatake & Kangari 1993). These rapid advances in computer

technology are generating opportunities for innovation in communications that have the potential to transform the construction industry through the integration of engineering design, construction and facilities management (Reinschmidt *et al* 1991).

Computer integrated construction (CIC) is the adaptation of computer integrated manufacturing (CIM) to the construction industry. Miyatake and Kangari (1993) presented an overall model for CIC (see Figure 3.33). Their model was divided into three main areas integrated via a central database:

1. integrated design and construction planning;
2. temporary on-site or permanent automated prefabrication factory system; and
3. site automation system (e.g. SMART, ABCS, MCCS, Big-C).

The integrated database may be used as a tool to improve communications and co-ordination between the client, architects, engineering consultants and construction contractors during the design and construction phases.

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3.10 Integrated construction automation systems

The fundamental differences between the dynamics of construction operations and those of the manufacturing industry pose significant difficulties to the successful deployment of automation and robotics. However, the Big-Six Japanese general contractors have developed integrated automated construction systems, which re-engineer the construction project environment to produce a more structured environment suitable for the deployment of automation and robotics. These systems amalgamate single task construction robots with material manipulators, measurement devices and central control centre to provide a complete automated construction system. The provision of a structured and predictable site environment aims to sustain a less hostile operational environment for automated construction technology. The repetitive and standardised procedures involved in multi-storey high-rise construction projects have been successfully automated and a range of demonstration projects has been undertaken within Japan. One of the greatest advantages of integrated construction automation systems is the conversion of construction sites from a human-system-dominated environment to a mechanical system dominated one (Obayashi 1992).

Integrated construction automated systems consist of four fundamental elements:

- *A temporary covered working platform and jacking system* - a fully enclosed temporary working platform provides a factory type environment within which all material manipulators and automated construction systems operate. The enclosed working structure facilitates protection from adverse environmental conditions and reduces the impact of the construction project upon the surrounding environment. The entire platform is constructed on hydraulic jacks and once each floor is

complete, these can be activated to raise the working platform to a suitable level for completion of the next floor.

- *Just-in-time (JIT) delivery of structural members and sub-assembled components* - a form of production management where stocks of components are not obtained until they are actually required. JIT management can cause construction to be delayed if a certain sub-assembly is not delivered in time, but this may expose sections of the construction prefabrication process, which are not working to the desired schedule.
- *Automated material handling system* - structural members and prefabricated subassemblies are identified using barcodes and then automatically transported from the unloading area (ground level) to their final position within the structure (working platform). Material manipulators automatically orientate and position the subassemblies and structural members
- *Centralised on-site integrated control centre* - an information management system monitors and co-ordinates the construction process. The system maintains a real-time inventory of structural components, working drawings, scheduling and progress. Furthermore, it monitors material manipulator operations, labour activity, safety and quality standards.

Table 3.2 presents a summary of the integrated construction automation systems, which have been deployed in the construction of high-rise structures in Japan. That general contractors can afford these expensive experiments is one of the great strengths of the Japanese construction industry, but until project finance data is openly available, it will prove difficult to accurately assess the feasibility of these systems. The following subsections provide a detailed description of two of the most successful integrated construction automation systems.

3.10.1 Shimizu Manufacturing by Advanced Robotics Technology

The Shimizu Manufacturing by Advanced Robotics Technology (SMART) system controls all phases of high-rise construction, including ground engineering, superstructure erection, M&E and interior finishing work. The system aims to reduce labour and management man-hour requirements and decrease the total construction period. Furthermore, the system reduces environmental pollution and greatly enhances site safety through providing a more structured operational environment, which is protected from adverse weather conditions. From the on-site computer integrated management control centre, materials are located and tracked using a bar coding system. Various systems for labour safety, quality control, scheduling, plant management, working drawing preparation and overall construction co-ordination are operated from the control centre. The SMART system cost approximately £5 million to manufacture, and the system has cost the Shimizu Corporation approximately £10 million to research and develop (Normile 1993).

Figure 3.34 shows the construction procedure using the SMART system. The roof of the completed structure is constructed on the ground floor. The operating platform for housing the material manipulators and additional automated systems is then constructed. The lifting mechanism is supported upon four hydraulic jacking towers, which are seated on the steel super-structure. Further to the operating platform being raised, the hydraulic jacks then seated upon the structural steelwork of the next floor. The operating platform weighs approximately 1200 tons and each lift takes approximately 1.5 hours. The operating platform is completely covered by protective sheeting which provides an enclosed working environment.

Figure 3.35 shows the application of the SMART system during the construction of the

Juruko Bank building in Nagoya, Japan. The 22 storey, 88m structure was started in 1991 and successfully completed in 1993. During the tenure of the project approximately 20% of working days would have been interrupted due to adverse weather conditions if traditional construction procedures were utilised. Many of the hazardous tasks associated with high-rise construction projects were eliminated and site safety was greatly enhanced through the introduction of automation, adverse weather protection and the adoption of the layered construction method (Maeda 1994).

Figure 3.36 depicts an interior view of the SMART system working platform showing the conveying system and the automated positioning of a structural steel member designed with insertion type connections and having the ability to be free standing upon insertion. In the background, the blue cylindrical object is one of the hydraulic-jacking towers. The material conveyance cranes have automatic release mechanisms, which allow cables to be detached without human intervention.

The welding of beam to beam and column to beam connections is undertaken automatically using welding robots as shown in Figure 3.37. The compact and lightweight (19kg) welding system allows easy handling and transportation. Owing to the high level of automation, it is possible to have one technician supervising up to three machines simultaneously, therefore, greatly reducing the required labour (Maeda 1994).

During the construction of the Juruko Bank, a 30% reduction in the man-hours required to construct the structure was realised (Normile 1993; Miyatake 1993; Maeda 1994). It was projected that the system may eventually lead to a 50% reduction in the man-hours required for a similar project and that savings will flow from man-power and construction schedule

reduction. The number of days required to construct each floor of the Juroku bank building was reduced from 9 to 5 days during the final stages of construction, due to improvements in the control software and the working methods and practices of the workforce. During the second application of the system on the Rail City Yokohama building, the SMART system is expected to reduce the construction period by 20 to 40% (Maeda 1994).

3.10.2 Automated Building Construction System

The Obayashi Corporation Automated Building Construction System (ABCS) allows work to continue independent of adverse weather conditions. A parallel material delivery system performs the vertical and horizontal transportation of structural components from the site delivery area to the construction operation level.

Figures 3.38 and 3.39 show a plan and cross sectional view of the ABCS super construction factory (SCF). The overall dimensions of the SCF vary depending upon the dimensions of the structure being constructed. The SCF framework supporting the cranes and material hoists consists of the structural steel, which will become the roof structure for the finished building. The climbing mechanism rests upon alternate *in-situ* structural columns. The uppermost section of each column is equipped with a locking hydraulic jack system. Further to the completion of two structural floors and exterior cladding, the SCF is automatically jacked upwards. The entire SCF system, including cranes and material hoists, weighs approximately 2200 tonnes. The SCF has two outer 13 tonne 360° rotating cranes and a central 7.5 tonne gantry type crane. Two internal 13 tonne material lifts are used for conveying structural materials from ground level to the operating floor of the SCF. Finally, a jib crane is positioned on the roof of the SCF for the positioning and placement of the exterior cladding panels and for the removal of the temporary SCF structure.

The robots utilised within the ABCS system are generally more automated versions of existing plant such as automatically guided cranes plus existing robots brought from the manufacturing industry, such as welders and automated guided vehicles for material handling. The ABCS control system allows the site manager to review construction progress, revise the programme of work and arrange the future delivery of materials without leaving the on-site office facility.

The ABCS system was first applied during 1994 in the construction of the Riverside Sumida residential building and was most recently implemented during the construction of the NEC Tamagawa Renaissance City building. Figure 3.40 and Figure 3.41 show an exterior and interior view the operational SCF during the construction of the NEC project. The NEC building consisted of a 28 storey (2 basement levels) steel and pre-cast concrete super-structure with a total floor area of 79,752m². Automated procedures included the erection and welding of the steel elements, the installation of prefabricated floor panels, the fitting of curtain walls and the jacking of the construction operation platform.

The ABCS system creates a more predictable site environment for the application of automated construction technology. The Obayashi Corporation claim to achieve labour savings, increased productivity and quality improvements through the use of their Automated Building Construction System (ABCS). The Obayashi Corporation claim that the construction schedule for a 30-storey structure can be reduced by three months and the schedule for a 40-storey structure can be reduced by six months. Figure 3.42 presents a comparison in construction schedule for three conventional high-rise construction projects and three high-rise projects using the ABCS system. Figure 3.43 shows a comparison of unit labour requirements of four construction projects undertaken by the Obayashi

Corporation. The first two projects utilised conventional high-rise construction techniques and the final two projects used the ABCS system. From this benchmarking study, it was found that the ABCS system reduced the on-site unit labour requirements by 61 per cent (Miyakawa *et al* 2000). It is evident that the ABCS system reduces on-site labour requirements when compared to traditional high-rise construction techniques. The standardisation of work through prefabrication, effective material delivery systems and the use of versatile workers contribute to greater overall productivity (Wakisaka *et al* 2000).

O-SICS (Obayashi Strategic Integrated Construction System) aims to incorporate the ABCS system within a total construction service package, from planning through design and construction to maintenance, integrating hardware and software to re-invent the construction process, working from a common, developing database (Evans 1996).

3.10.3 T-Up

The Taisei Corporation have developed a totally mechanised construction system known as the 'T-Up' system. The T-Up system concept utilises the constructed superstructure as a production platform and temporary support mechanism for the automated material manipulators. The superstructure is predominately pre-fabricated under strict quality-controlled manufacturing conditions. Once delivered to the project compound, these subassemblies are installed quickly and accurately.

The four possible variations of the T-Up system are shown in Figure 3.44. In variation (a), a central core structure is constructed to provide support (S) for the manipulator base (B). As the central core is constructed and the T-Up system is hydraulically raised, the outer superstructure is then completed. The overhead cranes position and place beams, columns,

pre-cast floors, wall sections and other subassemblies. Further to the completion of the main structural components for each floor, material manipulators and interior finishing systems complete the installation of M&E services and aesthetic finishes. Once the structure is complete, the “hat” section becomes incorporated within the completed structure.

Figure 3.45 shows the T-Up system being used during the construction of the Mitsubishi Heavy Industries Yokohama building. The 35 storey steel and pre-cast concrete structure was successfully completed in March 1994. During the project, a construction productivity rate of one storey per three days was achieved. The entire project was completed in 24 months over the estimated construction period achievable using conventional high-rise construction techniques of 30 months (Sakamoto & Mitsuoka 1994). Of the 24-month contract, only 6 months were required for the construction of the 35 steel super-structure. The ability to prefabricate structural modules off-site under controlled conditions by machines ensures the contractor and the client a high quality finished product (Levy 1993).

Desk-top computer and hand-held data entry terminals are utilised during the implementation of the T-Up system. A 3-D computer package is used to display construction progress to site engineers located within the site office. The entire structure can be viewed from a distance or sections can be examined in detail. Furthermore, it is possible to view the interior of the structure and examine the contents of each structural floor. Construction progress can be monitored in real time facilitating more efficient scheduling and construction planning. The T-Up method allows the site manager to concentrate on a degree of quality control not possible with traditional piecemeal construction sequences.

The Taisei Corporation are currently upgrading the T-Up system by implementing automatic measurement and adjustment systems and by introducing steel welding robots. Figure 3.46 shows a prototype automatic beam and column connection welding robot. Furthermore, the Taisei Research Institute are working on the unification of design stage drawings of members and materials with the construction schedule.

3.10.4 Roof Push-Up system

The Takanaka Corporation Roof Push-up construction method involves the construction of the top floor and roof structure at ground level and then hydraulically jacking it upwards as each of the lower floors are constructed. The Roof Push-up jacking system consists of floor and column jacks. These hydraulic jacks are used interchangeably to lift the roof structure and the construction floor.

An overhead 360° circular gantry crane was developed to orientate, position and place structural elements. Additionally, air cushioned material transporters are used to move elements horizontally across the construction floor.

The on-site central control system consists of the following elements:

- operation monitoring system monitors work in progress over the entire project;
- communication subsystem is used to instruct operative directly working on the construction floor or the partially finished floors below; and
- precision monitoring system provides real-time monitoring of structural element installation.

The system was successfully applied to the construction of the Yanagibashi Mitsui Building in Nagoya, Japan. The 12-storey structure was completed in 1991. During the project a construction period of 6 days per structural floor was established. Furthermore, the Takanaka Corporation claimed that unit labour requirements were reduced from 0.25 man/m² to 0.17 man/m². Therefore, it was concluded that overall labour productivity was improved when compared to traditional high-rise construction procedures (Morita *et al* 1993).

3.10.5 Mast Climbing Construction System

The Maeda Corporation Mast Climbing Construction System (see Figure 3.47) has a similar configuration to the SMART and ABCS systems. The MCCS system is composed of five sub-systems: the MCCS production control system, climbing system, material conveying system, assembling system and a measurement system. In a similar fashion to the SMART and ABCS systems, the uppermost floor of the finished structure is constructed on the ground and covered with a temporary enclosure. Further to completion of the working floor the climbing mechanisms, material conveyance robots, measurement equipment and control room hardware are installed within the working floor area. The MCCS system incorporates two 4.7 tonne 360° rotating cranes and an internal vertical material hoist (see Figure 3.48). These are used in the conveyance and final positing of structural steel members and pre-fabricates units. Once each floor is complete, the climbing systems raise the working floor so that the next structural floor can be completed. Once the uppermost floor is reached, the MCCS system is dismantled and the finished structure remains.

The advantages of using the MCCS system include:

- increased operative safety during the erection of structural steel members;
- shortening of the construction period;
- reduction in on-site labour requirements; and
- the working shelter eliminates production stoppages due to poor weather conditions and reduces environmental pollution from construction operations.

Having only been used on two construction projects, the MCCS system has yet to provide the operational efficiencies experienced through the use of the SMART and ABCS systems.

3.10.6 Big-Canopy

The Obayashi Corporation Big-Canopy (Big-C) system is similar to the ABCS system, i.e. both systems aim to integrate mechanisation, automation, prefabrication within an all-weather construction environment utilising versatile construction operatives. However, according to Wakisaka *et al* (2000) the Big-C system differs from the ABCS system in the following ways:

1. It is difficult to raise the level of automation in reinforced concrete construction when compared to steel construction in terms of cost. For reinforced concrete construction, greater manual input is required for connecting reinforcement bars and erecting/dismantling temporary shuttering.
2. It is difficult to provide an all-weather assembly plant for reinforced concrete construction as the concrete requires time to cure.

Wakisaka *et al* (2000) and Furuya *et al* (2000) describe the main features and benefits of the Big-C system:

- improved productivity of overhead cranes when compared to traditional tower cranes. The parallel material delivery system decreases the cycle times required for the delivery and erection of the pre-fabricated elements;
- the quality of construction work is increased through prefabrication and the integration of all assembly procedures;
- the construction period is reduced through the use of prefabrication and the ability to continue construction work during adverse weather conditions;
- a high degree of design freedom. As the temporary supports for the roof structure are independent of the finished structure, the Big-C system may be applied to varied structural configurations;
- the effects of adverse weather conditions are minimised: the effect of direct sunlight, wind, rain are moderated and site operatives are able to work directly under the temporary roof;
- prefabrication reduced the volume of debris generated during the construction process; and
- the system allows the overall construction costs to be reduced.

The Big-C system utilises a combination of pre-cast and in-situ concrete with modularised subassemblies. Pre-cast components include columns, beams, slabs and interior wall elements. Additional pre-fabrication includes vertical and horizontal drainpipes, air conditioning ducts, low current indoor cables and wooden interior partitions. Figure 3.49 shows the pre-cast modular construction system used in conjunction with the Big-C system.

The Big-C system, as shown in Figure 3.50, consists of a large construction lift for vertical material delivery and automated overhead cranes for horizontal delivery and structural element orientation and positioning. The central overhead crane collects materials from the vertical hoist and passes them onto the right or left cranes, materials are then automatically positioned in the appropriate location. During the final placing of structural elements, overhead material cranes are operated from the construction floor via handheld radio control units. However, acceleration and deceleration are controlled automatically to avoid accidental damage of the components. Consequently, worker and delivery system idle time is reduced with increased delivery and erection cycle times. A suspension unit (GYAPTS) to control the rotation of building materials caused by wind and inertia following crane movements was developed to allow materials to be manipulated with a high degree of response and to stop them at the precise angle required for erection. The GYAPTS suspender device is used to suppress load rotation and position the structural element at a desired angle (Inoue *et al* 2000a). The entire Big-C system is housed underneath a synchronously climbing temporary roof structure.

The synchronously climbing temporary roof structure consists of four tower crane posts positioned independently of the footprint of the building under construction (see Figure 3.51). The frame is designed to withstand high wind loading and dynamic loading induced by severe earthquakes. The entire weight of the roof frame, climbing device, overhead cranes and jib crane is approximately 600 tonnes. The roof structure is raised two floors at a time at a rate of 300 mm/min.

The Big-C system was initially utilised on a 26 storey high-rise pre-cast concrete residential building within the Chiba prefecture of Tokyo. The Big-C system reduced erection cycle

times, reduced on-site labour requirements. The number of operatives engaged in the erection work was 65% of pre-cast construction techniques and 25% of traditional piecemeal reinforced concrete construction techniques (Wakisaka *et al* 2000). The Obayashi Corporation have compared the Big-C system with traditional pre-cast concrete construction, the system form-work method and traditional *in-situ* reinforced concrete construction. Figure 3.52 compares the labour man-days per unit floor area (man-day/m²) of the superstructure erection work with their alternative construction techniques. It is evident from this benchmarking study that the Big-C system greatly enhances labour productivity and significantly reduces overall project labour requirements. The working environment was improved through reducing the surface temperature of operatives and their work environment. The recorded roof to outdoor temperature difference was approximately 10°C on the labourer's clothes and 25°C on reinforcement bars. The temporary roof structure greatly reduces the physical load placed upon operatives due to environmental conditions.

The Obayashi Corporation found that out of all the high-rise structures authorised by the Building Center for Japan, over the period 1986 to 1995, 82% (119) of the structures could have been constructed using the Big-C system (Wakisaka *ibid*). With each new application of the Big-C system, the Obayashi Corporation expects improvements in efficiency and greater reduction in construction costs. The system provides a structured environment for the future deployment of more advanced construction manipulators and control systems.

3.10.7 New SMART

Further to the development of the SMART system, the Shimizu Corporation have refined the original system to reduce the operational complexity and facilitate greater construction

productivity. Figure 3.53 shows the New SMART system being used in the construction of the Makauhari SH-1 condominium project from November 1998 to March 2001. Results from this implementation project have yet to be published. However, the Shimizu Corporation has already utilised the New SMART system in the construction of the HDB Center in Singapore. This provides an early indication of the successfulness of the New SMART system in the construction of high rise structures.

3.11 UK implementation projects

The following sub-sections present details of two tele-operated construction mechatronics technologies, which have been successfully implemented on operational construction projects. These case studies provide an indication of the nature of the mechatronics technology being used on UK construction projects. However, the information provided is not exhaustive and does not represent all advanced technologies being used on UK construction projects.

3.11.1 Meadowside granary demolition project

As part of the Clydeside development project, Glasgow city planners are regenerating a 120 acre stretch of the river Clyde. The development project involves the controlled demolition of the Meadowside granaries. The three Meadowside granaries, in which grain from all over the world was stored for distribution throughout Britain, were built from masonry and reinforced concrete between 1914 and 1968. These grain stores eventually became surplus to requirements. Owing to the city center location of the structures and their height, the use of explosives was eliminated. In order to conduct a controlled demolition, Scotdem Ltd and

sub-contractor Corecut Ltd, have employed BROKK BM180 tele-operated demolition manipulators (see Figure 3.54).

These units are designed to be compact and highly mobile enabling them to be transported into confined space to undertake controlled demolition. The machine was powered by an external generator and connected with an umbilical power cable. The machine consists of a three part hydraulic boom fitted with a hydraulic hammer, which is attached to the 360° rotating crawler track base. The units are remotely controlled via a portable control panel, which enables the operator to work at a safe distance from the machine and any falling debris. Subsequently, the machine operator is liberated from exposure to vibrations and exhaust gases. The BROKK AB product range includes a selection of end-effectors, which can be mounted in the boom. These include crushing jaws, loader buckets, backhoe buckets and clamshell buckets. According to Scotdem Ltd, the highly versatile machine is capable of demolishing between 15 and 30 m³ of reinforced structural concrete per day. The BM180 machine has provided an extremely safe and economical solution for the controlled demolition of the Meadowside granaries.

3.11.2 Holborn Place Daily Mail project

GGR Glass Services are a major supplier and hirer of vacuum lifting equipment for the UK construction industry. In order to overcome the inherent difficulties associated with situations such as overhead glazing, cladding under overhangs and in difficult to reach locations, the ergonomic manipulating unit (EMU) was designed to provide an economical solution to execute these activities independently of scaffolding and craneage. The EMU system consists of a HIAB 26T crane combined with four 300mm Pannkoke vacuum suction cups and a unique patented multi-positional head. The EMU system requires a

110V 32A power supply to drive the hydraulic motors. The manipulator is operated via a joystick located on the frame of the system. Outriggers are provided to prevent the unit toppling whilst manipulating loads out with the chassis track. With a 2.1m and 3.1m jib length the EMU system can handle loads of up to 500kg. Using a 4.2m jib, the system can handle loads of up to 300kg. A mechanical safety restrictor is provided that requires a conscious action by the machine operator to allow the use of the greatest reach.

The EMU system is primarily used for fitting glazed units. However, the system has been used to position and place a variety of alternative materials such as steel and aluminum plates and panels, stone and concrete elements. The EMU unit provides direct savings through increased productivity whilst allowing tower cranes and scaffolding to be managed more efficiently. Allowing cladding and glazing to be undertaken in areas previously unlikely to be considered, architects may consider new and innovative uses of glass of greater size and weight. Figure 3.55 shows the EMU system being deployed by SN Murdoch Ltd in the erection of the exterior glazing for the Daily Mail building in Holburn Place, London.

3.12 Humanoid construction operatives

There is considerable demand for humanoid robots capable of undertaking complex tasks to support humans in everyday industrial activities. In 1998, the Agency of Industrial Science and Technology (AIST) and the Ministry of International Trade and Industry (MITI) commenced a five-year humanoid robotics research and development project. The platform-based approach consists of a humanoid robot (see Figure 3.56) developed by Honda Research & Development Ltd and a tele-presence spatially correspondent control cockpit (see Figure 3.57) developed by Kawasaki Heavy Industries Ltd., Matsushita Electric Works Ltd., Fanuc Ltd and the University of Tokyo (Inoue *et al* 2000b). Fujitsu, Hitachi

and the University of Tokyo have also developed a virtual humanoid robot platform (Nakamura *et al* 2000). The virtual computer simulation allows the dynamics of the machine-environment to be modelled. The technology allows complex operations to be accurately modelled before the actual system is introduced. The development of a general application system rather than a specific single-task machine was a prime objective. Though the system is currently only an advanced prototype, the potential application throughout hazardous industries is endless.

The AIST/MEL humanoid research programme aims to advance the library of basic motions for the humanoid robot system. The use of humanoid systems to eventually displace machine operators and conduct general construction tasks appears to be a future direction for construction automation. Through developing a universal humanoid machine, capable of executing a varied workload, dangerous and debilitating construction procedures may be performed under remote control whilst observing stereoscopic images of the working environment. Possible applications for the system include plant operation, welding, material handling, disaster recovery, nuclear industry operations, care and security services. However, it may be argued that complex bi-pedal walking motions may be unnecessary for construction mechatronics applications.

3.13 Conclusions

The current research shows that it is possible to automate a broad range of traditional construction site activities using existing mechatronics capabilities. From the review of the state-of-the-art technology and the focus group studies, the following conclusions can be drawn:

1. Japanese contractors have significantly reduced their construction automation and robotics research programmes with regards to investment and allocation of research staff.
2. Japanese general contractors are not realising the tangible benefits perceived during the construction automation R&D programmes initiated from the early 1980's.
3. The use of fully autonomous single-task construction process technology is proving to be inherently complex and prohibitively expensive. Therefore, man-machine technologies are proving to be more successful in mechanising construction site operations.
4. The development of integrated automated construction systems (e.g., ABCS, SMART, MCCS, T-Up etc) has proven to provide an operational environment more suited to the operations of automated material process technologies. However, their complexity has been reduced in order to increase their economic viability and ease of application.
5. Ongoing Japanese research aims to further the development of multi-task technologies and computer integrated construction systems, which incorporate automated off-site pre-fabrication with construction erection systems.
6. Japanese contractors are primarily concerned with operational safety, improving the construction project environment and the strategic value of learning. Importantly, Japanese contractors are aware of their strategic competitive advantage with regards to

their previous experiences with the deployment, operation and maintenance of automated construction process technologies.

7. There is a considerable range of tele-operated construction plant being utilised on UK construction projects. However, there has been minimal use of automated technologies on operational construction projects. Further research is required in order to gain greater understanding of the innovative plant and machinery currently being utilised on UK construction and civil engineering projects.
8. Civil engineering operations involving heavy, hazardous and onerous work conditions are they provide opportunities for the deployment of automation and robotics. The nature of the materials (generally heavy, oversized and expensive) utilised generates a demand for material conveyance and positioning systems, which can eliminate health and safety hazards and provide improvements in site productivity.
9. Single-task automated construction technology has not provided the anticipated labour reductions and increased site productivity due their complex operational requirements and their inability to provide high rates of utilisation through a lack of industry demand.
10. Rather than developing construction automation systems specifically for their tasks, the use of off-the-shelf manipulators and standard components may provide a more economical solution to the development of automation and robotics systems for the construction industry.

11. The combination of off-site industrialised prefabrication and integrated automated construction provides significant economies in high-rise construction. Furthermore, the development of more sophisticated automated construction erection and interior finishing systems may provide even greater site productivity and labour reductions than presently experienced.
12. Japanese construction contractors have imitated and emulated each other's construction automation research and development strategies. Technologies are apparently developed, firstly, in order to display technological prowess and, secondly, to provide competitive advantages. However, Japanese general contractors are successfully managing to deploy automation and robotics within operational construction environments.
13. Within the United Kingdom, various tele-operated and man-machine systems are already providing increased operative safety, work efficiency and increasing the productivity of their associated operations. Two case studies were presented within this Chapter.
14. The successfully applied automated systems presented within this Chapter are primarily providing increased site operative safety with secondary tangible benefits including increased productivity and quality.

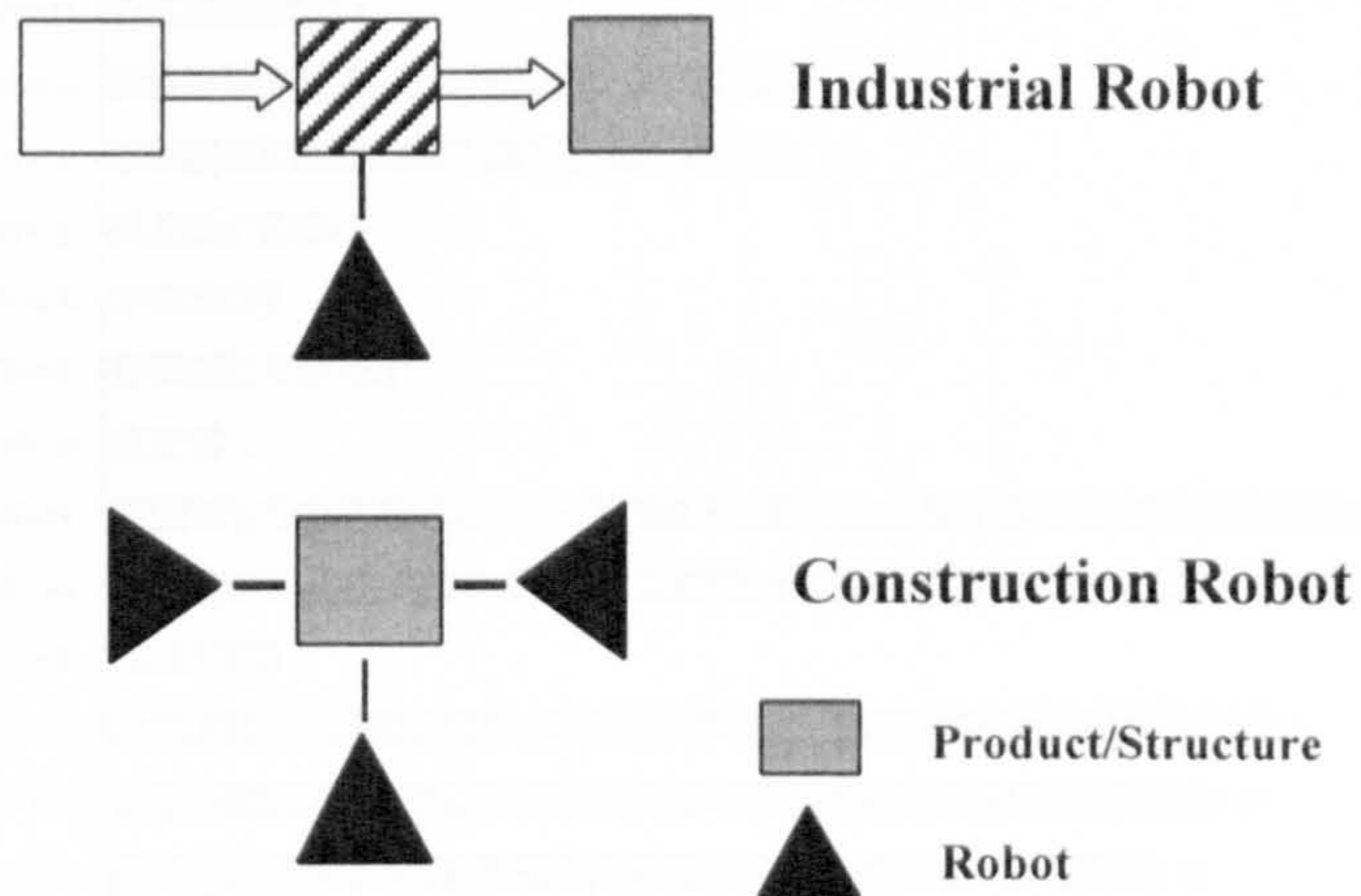


Figure 3.1: Manufacturing vs construction robots
 Source: Cousineau & Miura 1998

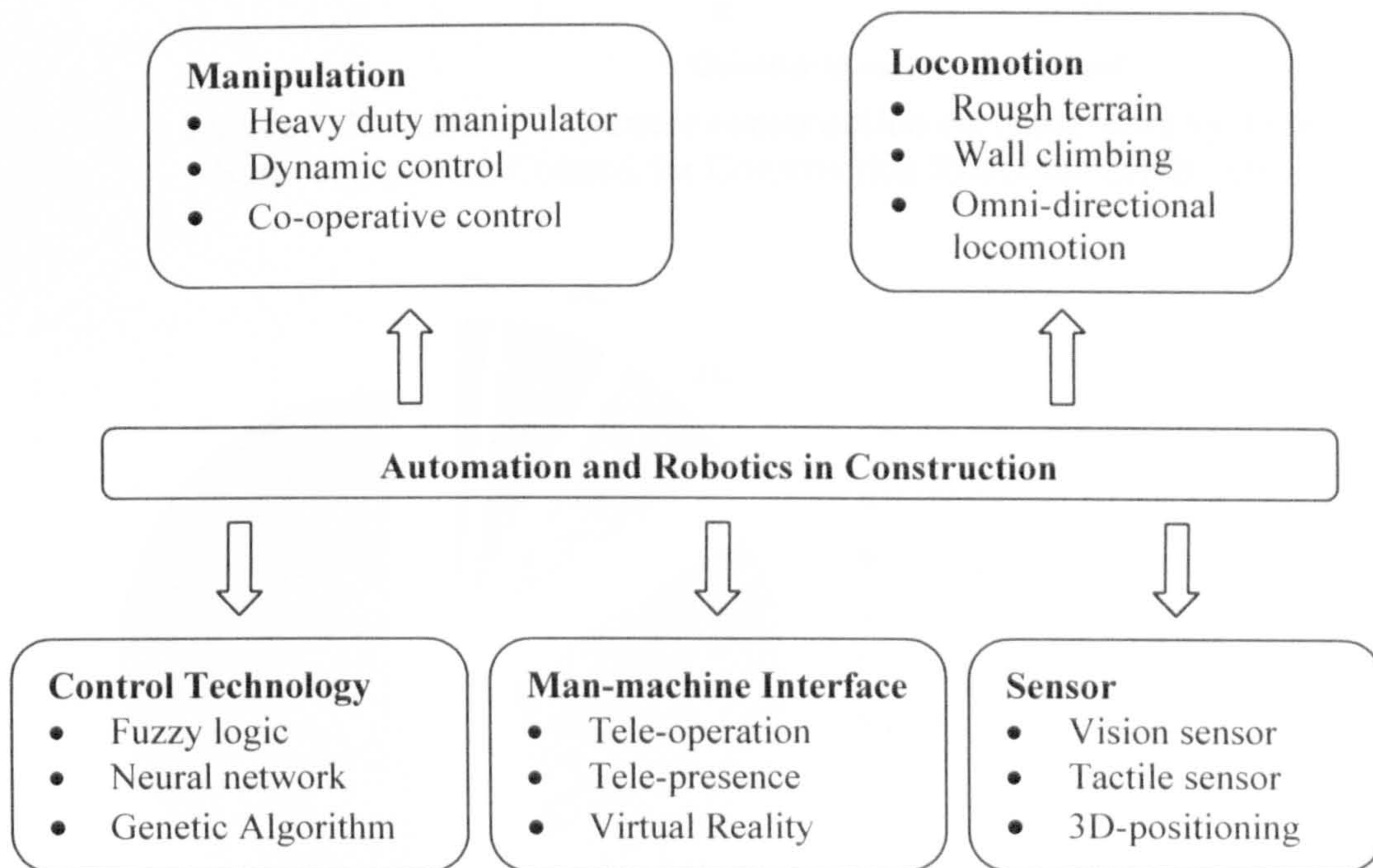


Figure 3.2: Basic technology for automation and robotics in construction
 Source: Ueno 1994

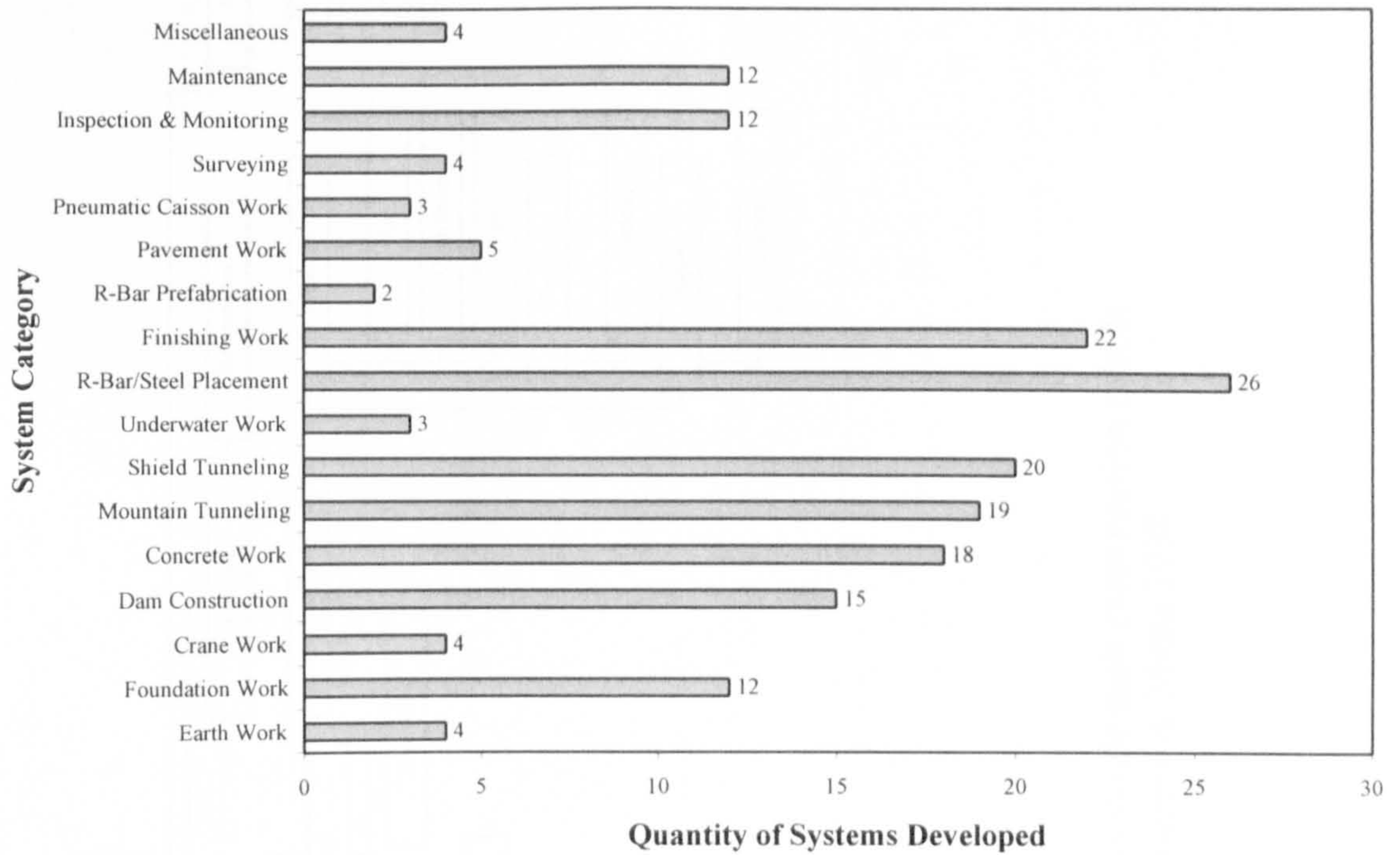


Figure 3.3: Existing Japanese construction mechatronics systems
 Source: Japanese Council for Construction Robot Research 1999

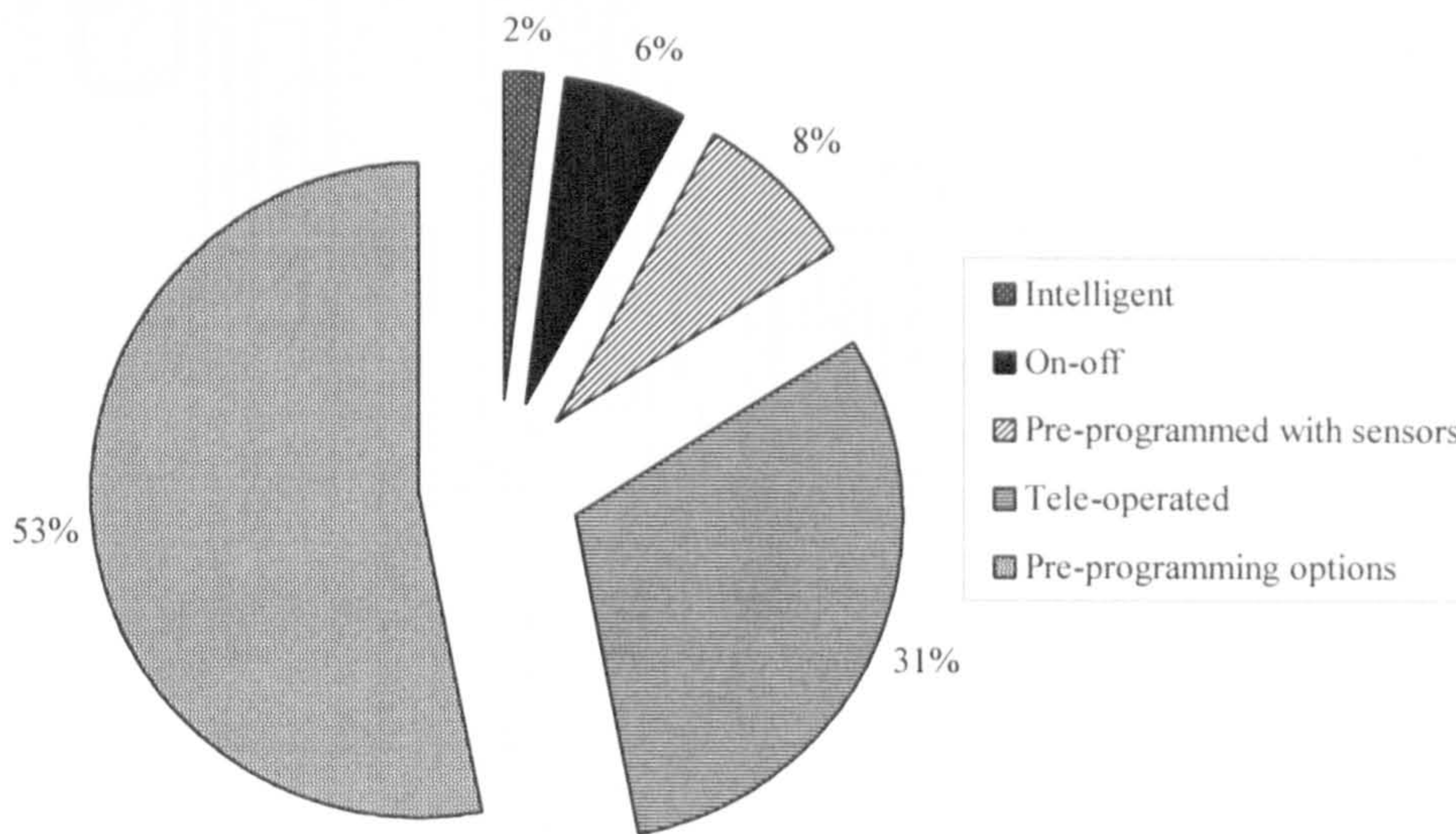


Figure 3.4: Breakdown of construction automation control systems
 Source: Warszawski & Navon 1998

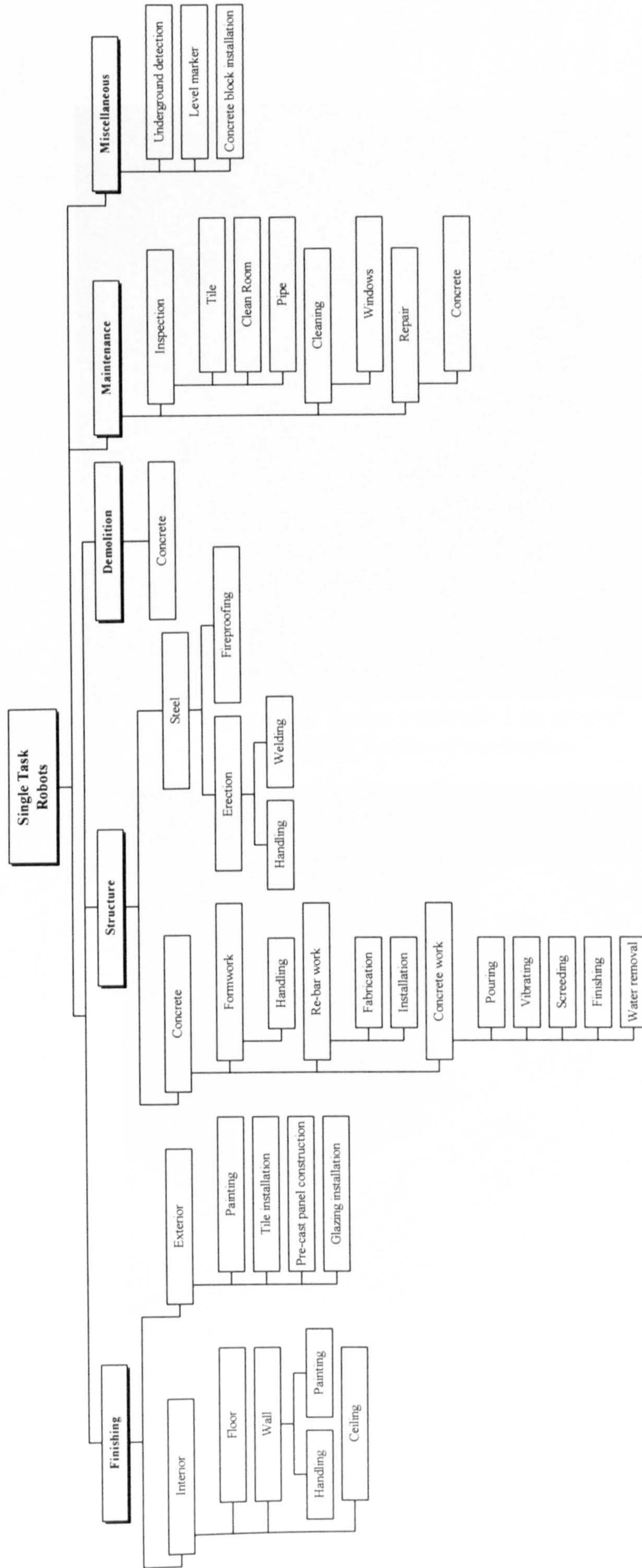


Figure 3.5: Categorisation of Japanese single-task construction robots
 Source: adapted from Cousineau & Miura 1998



Figure 3.6: Radio controlled excavator
Courtesy: Kajima Corporation



Figure 3.7: Radio controlled tele-operation
Courtesy: Kajima Corporation



Figure 3.8: Horizontal concrete distributor
Courtesy: Takanaka Corporation



Figure 3.9: Tele-operated concrete boom pump
Courtesy: Putzmeister UK Ltd

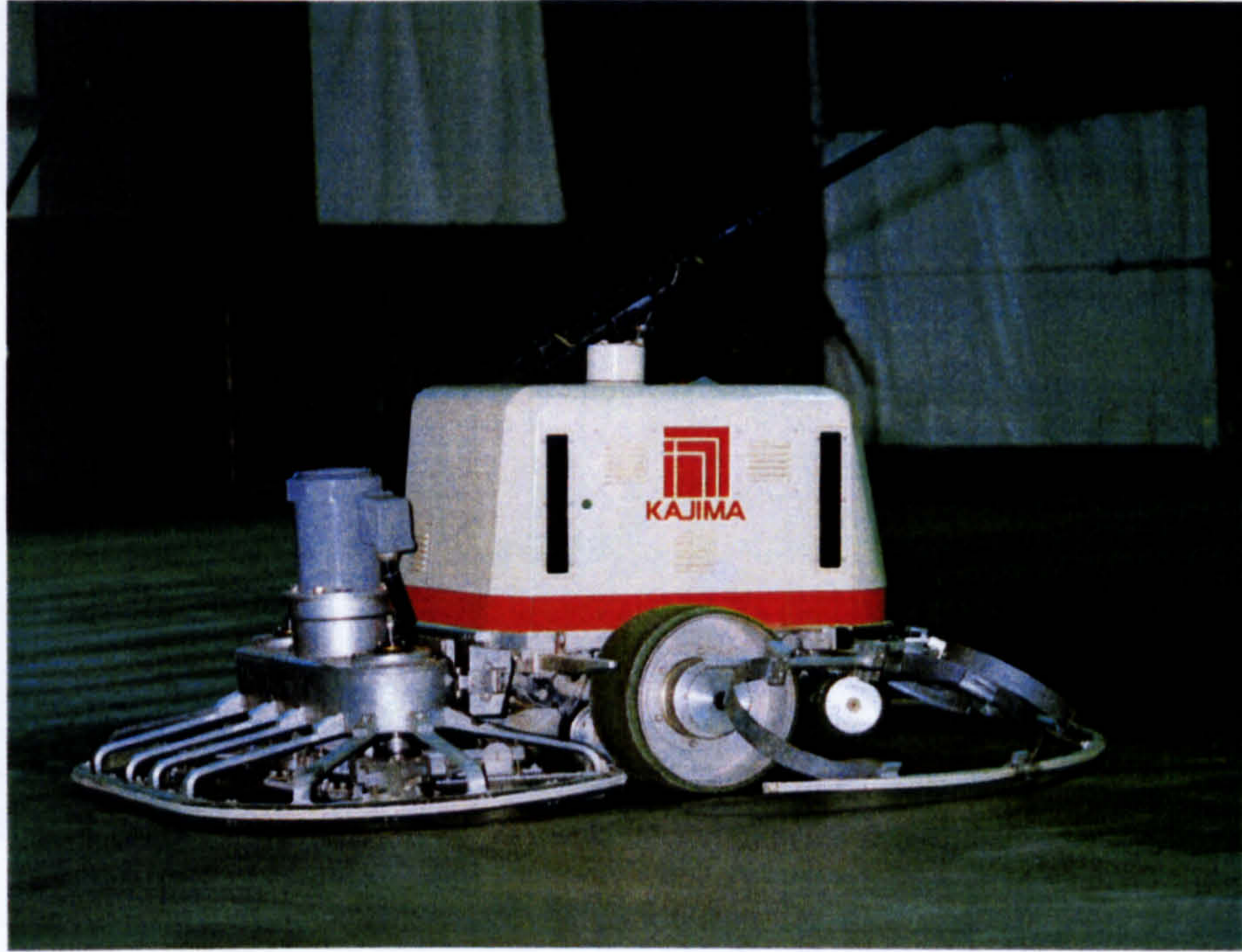


Figure 3.10: Kote-King autonomous concrete slab finishing robot
Courtesy: Kajima Corporation



Figure 3.11: Robocon, tele-operated concrete trowelling system
Courtesy: Tokimec Construction Systems Inc & Takahashi Construction Systems Inc.

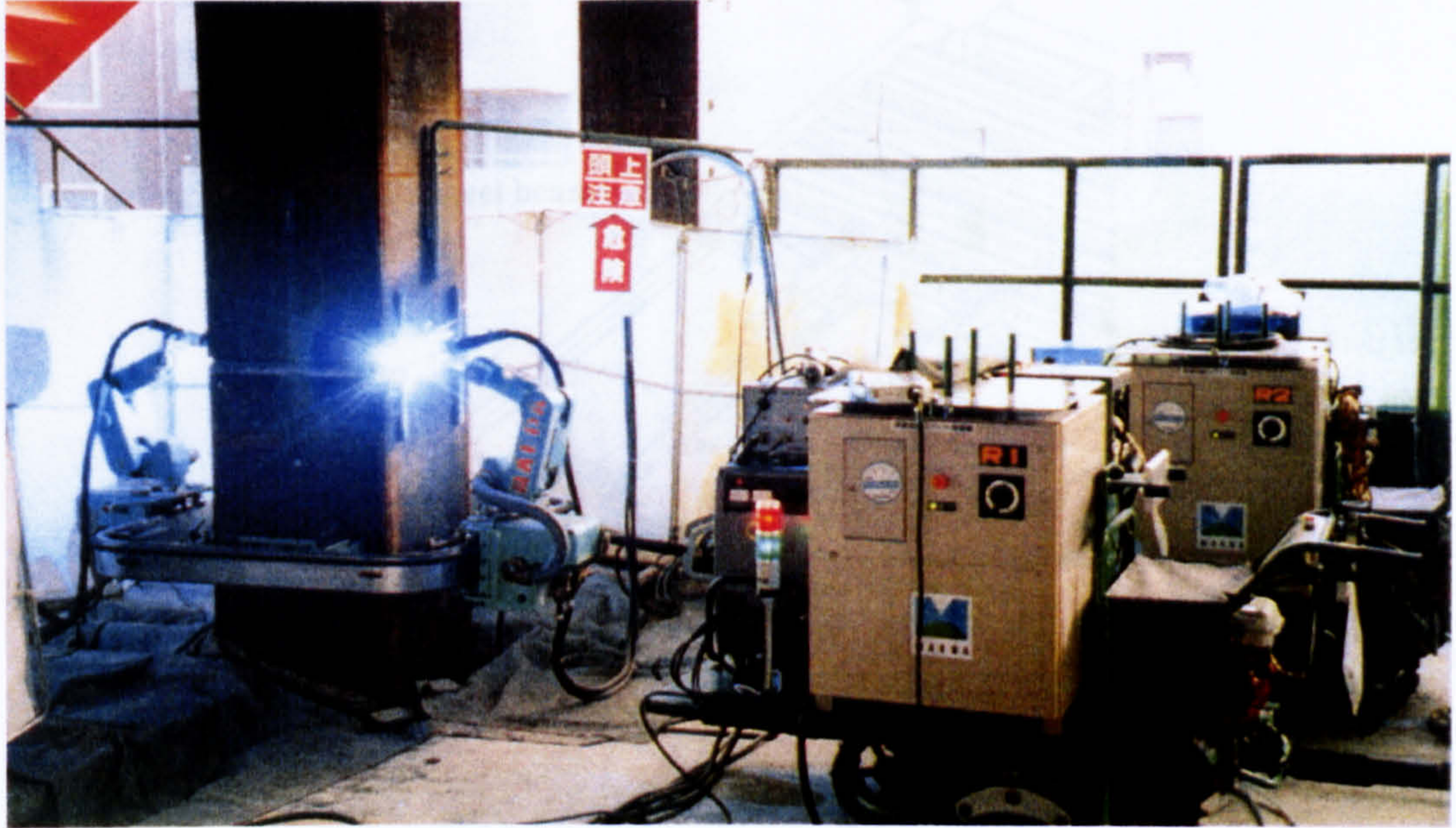


Figure 3.12: Site column welding robot
Courtesy: Maeda Corporation



Figure 3.13: Lightweight material manipulator
Courtesy: Tokyu Construction Co. Ltd.

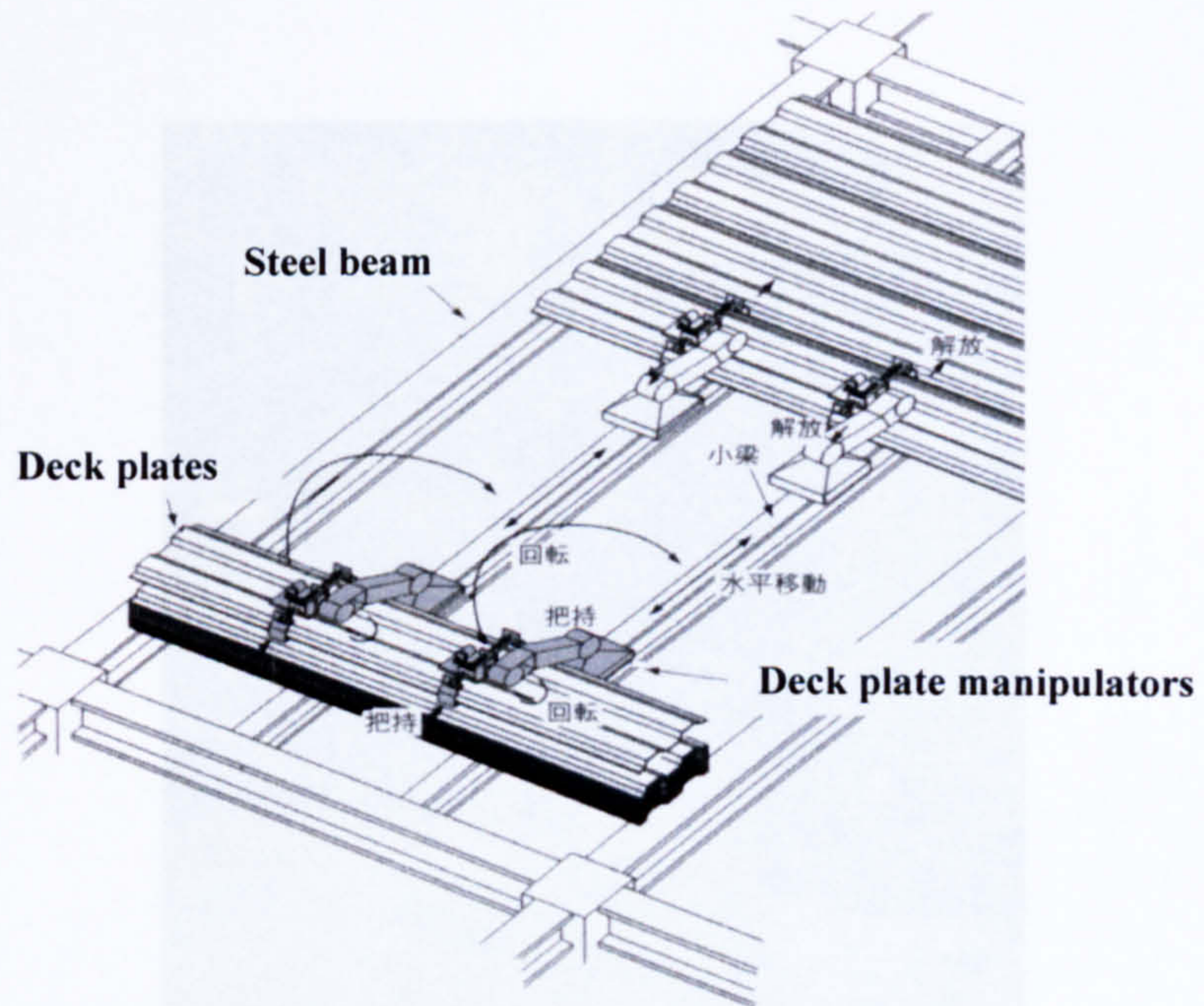


Figure 3.14: Deck Mouse, composite steel-floor deck placement system
Courtesy: Kumagai Gumi Co. Ltd



Figure 3.15: Kuka KR210 heavy-duty manufacturing manipulator
Courtesy: University of Stuttgart, ISW

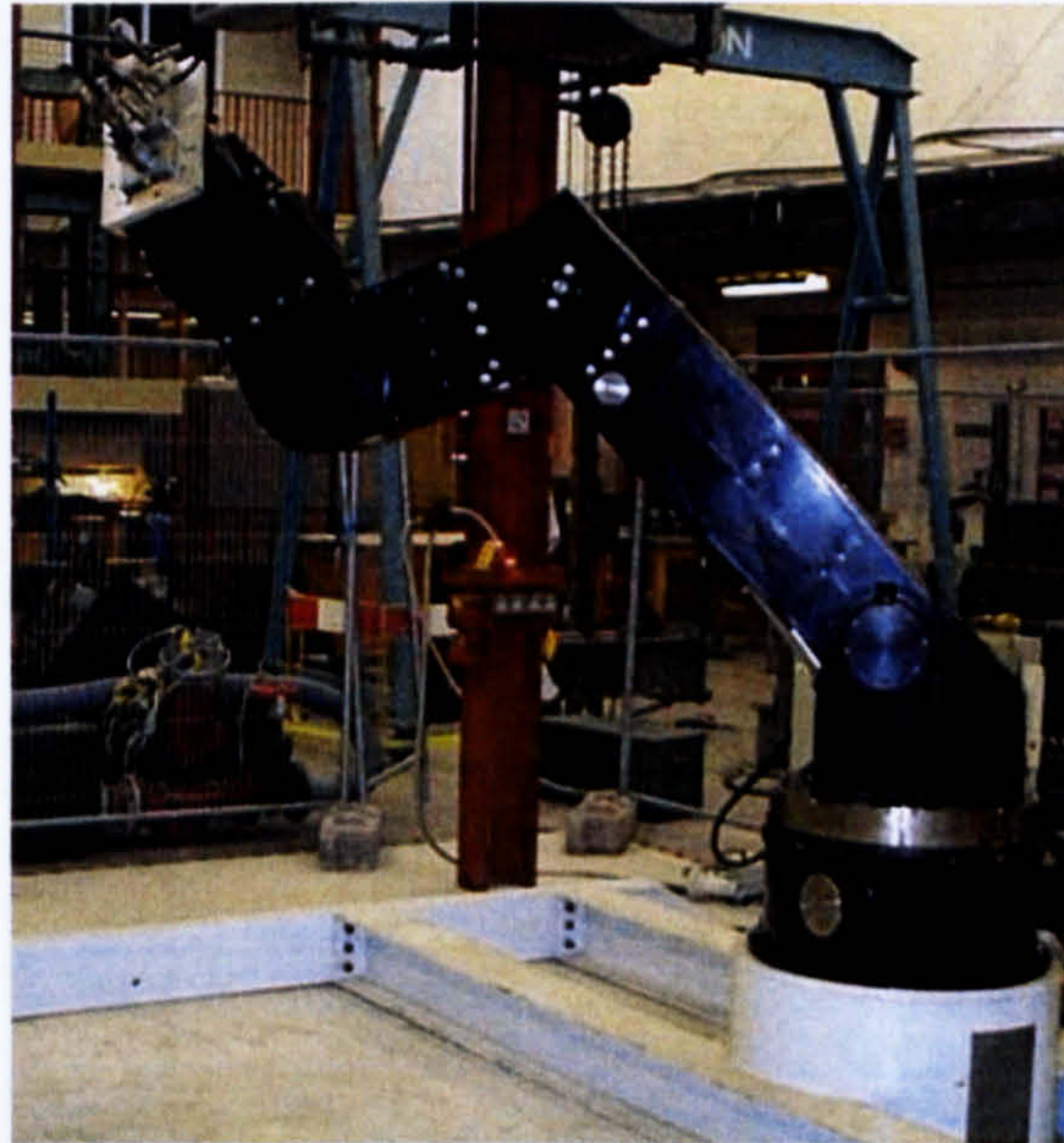


Figure 3.16: Prototype Starlifter[®] heavy tool deployment manipulator
Source: Zied *et al* 2000

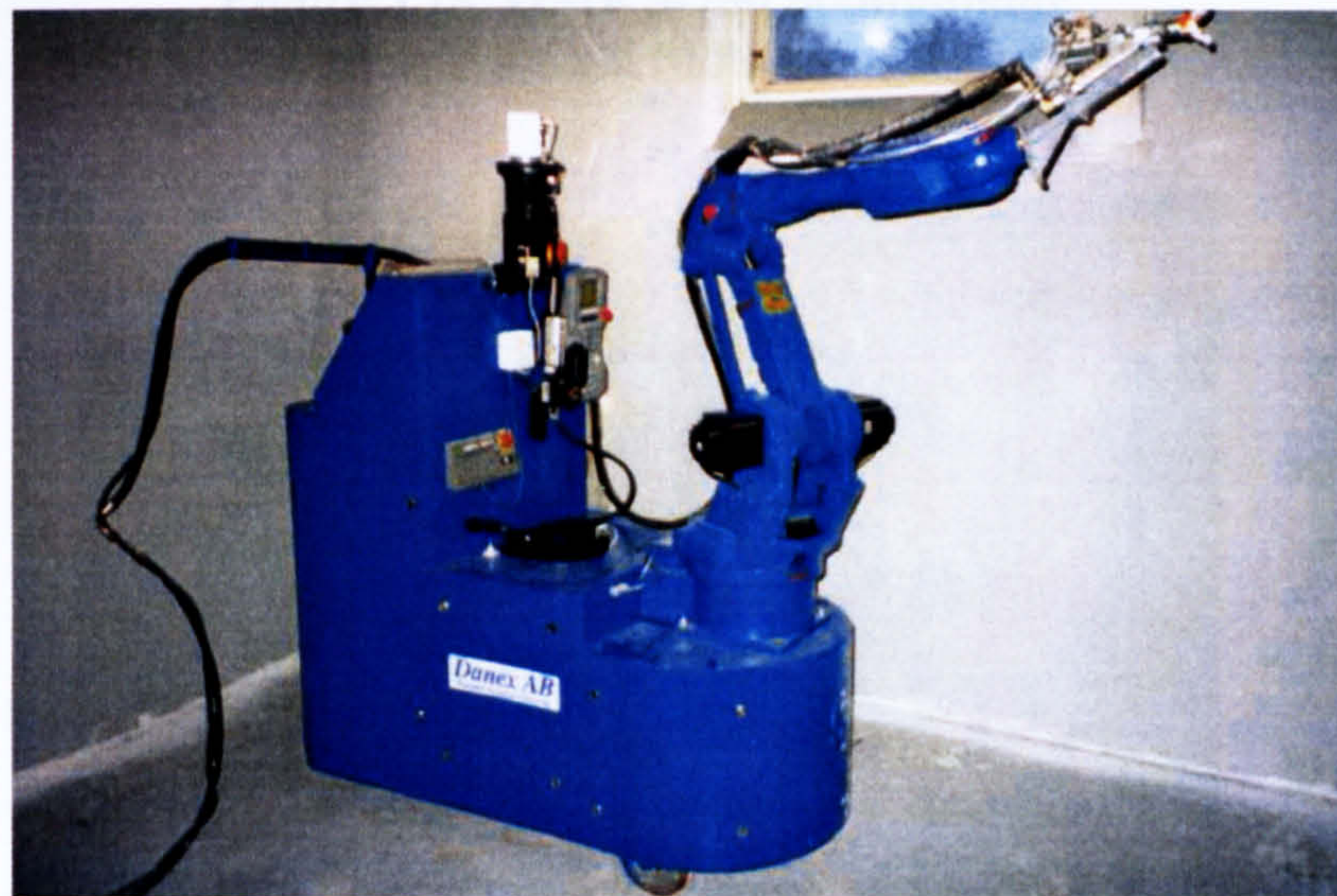


Figure 3.17: Mobile Robotics AB, prototype autonomous plastering robot
Courtesy: Mobile Robotics AB

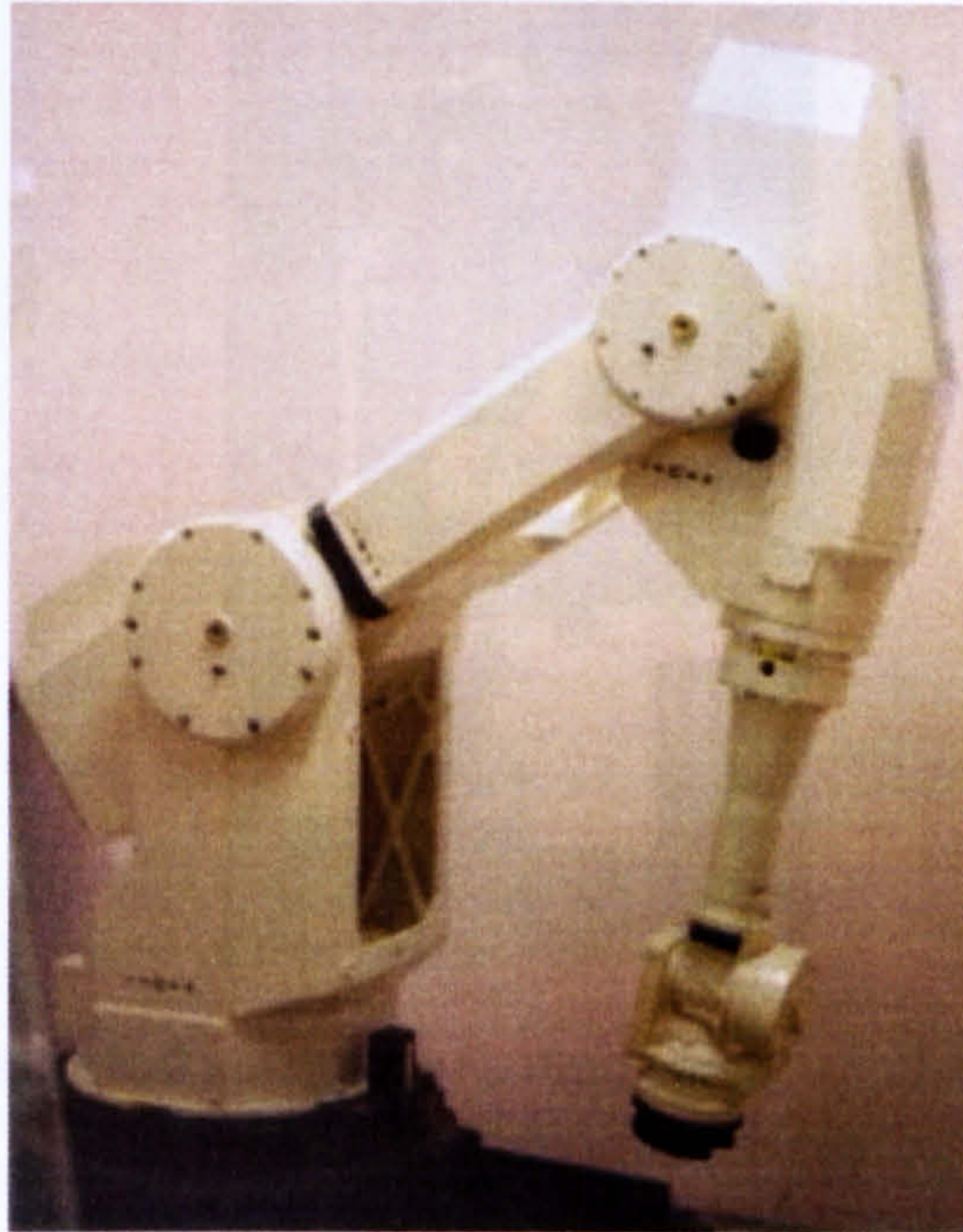


Figure 3.18: GMF S-700 manipulator
Courtesy: General Motors Funac Ltd

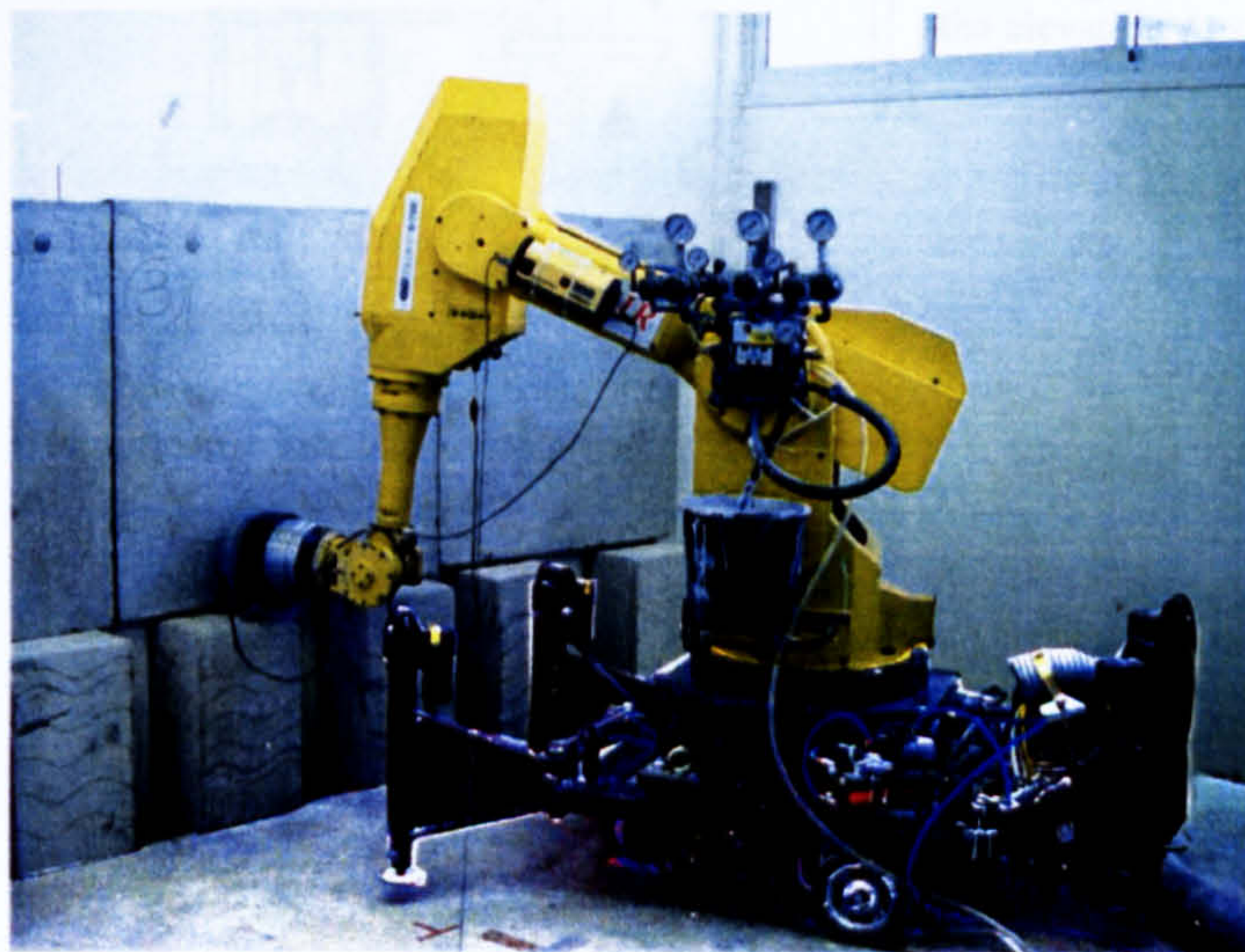


Figure 3.19: Technion autonomous multi-purpose interior robot (TAMIR)
Courtesy: Technion Institute of Technology



Figure 3.20: SSR-3 steel fireproofing spray application system
Courtesy: Shimizu Corporation

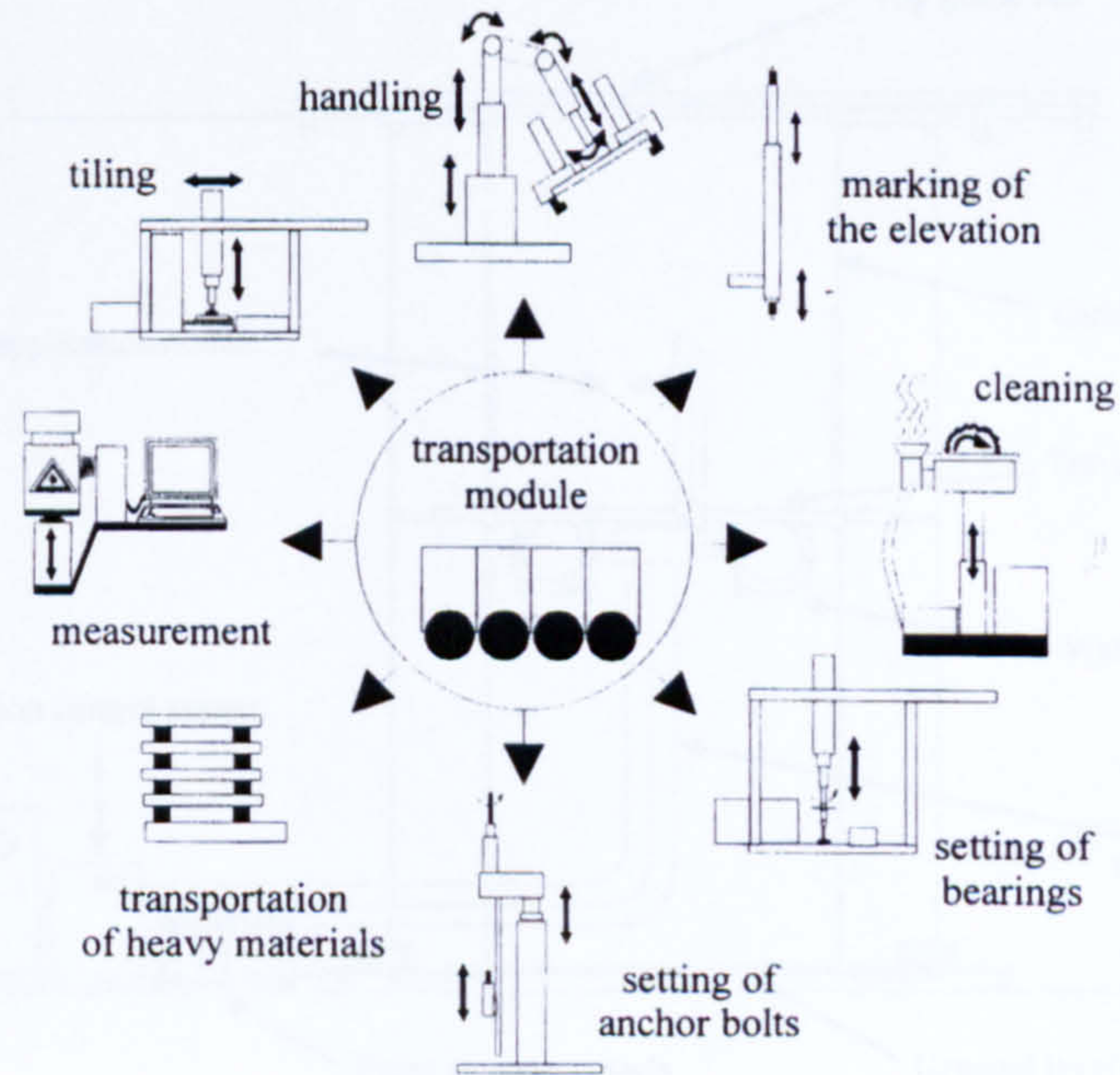


Figure 3.21: Modular concept for automated interior finishing processes
Source: Feldmann & Kock 1998



Figure 3.22: Prototype modular construction robot system
Courtesy: TU München, Lehrstuhl br+i

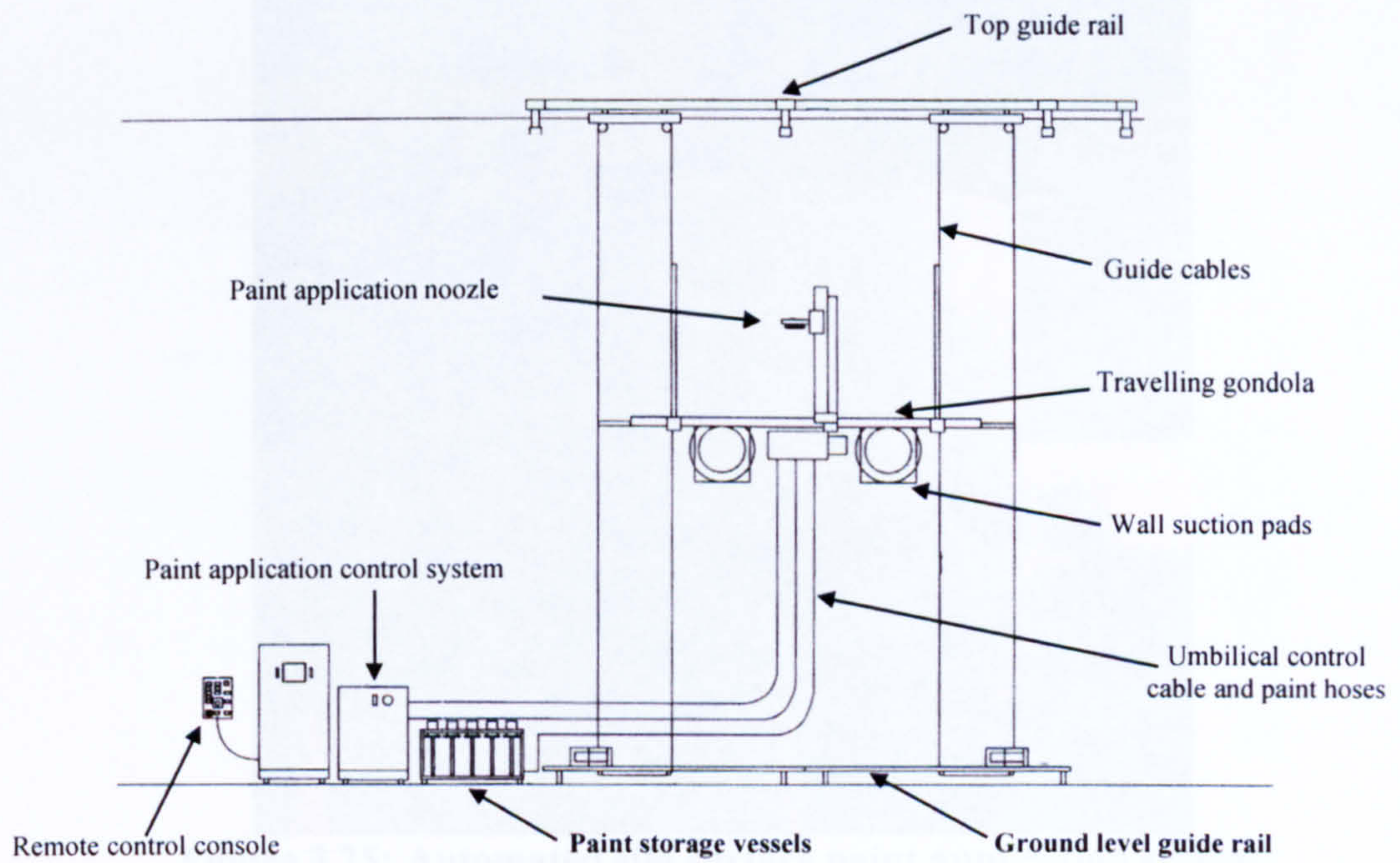


Figure 3.23: Exterior paint application system
Courtesy: Tokyu Construction Co. Ltd.

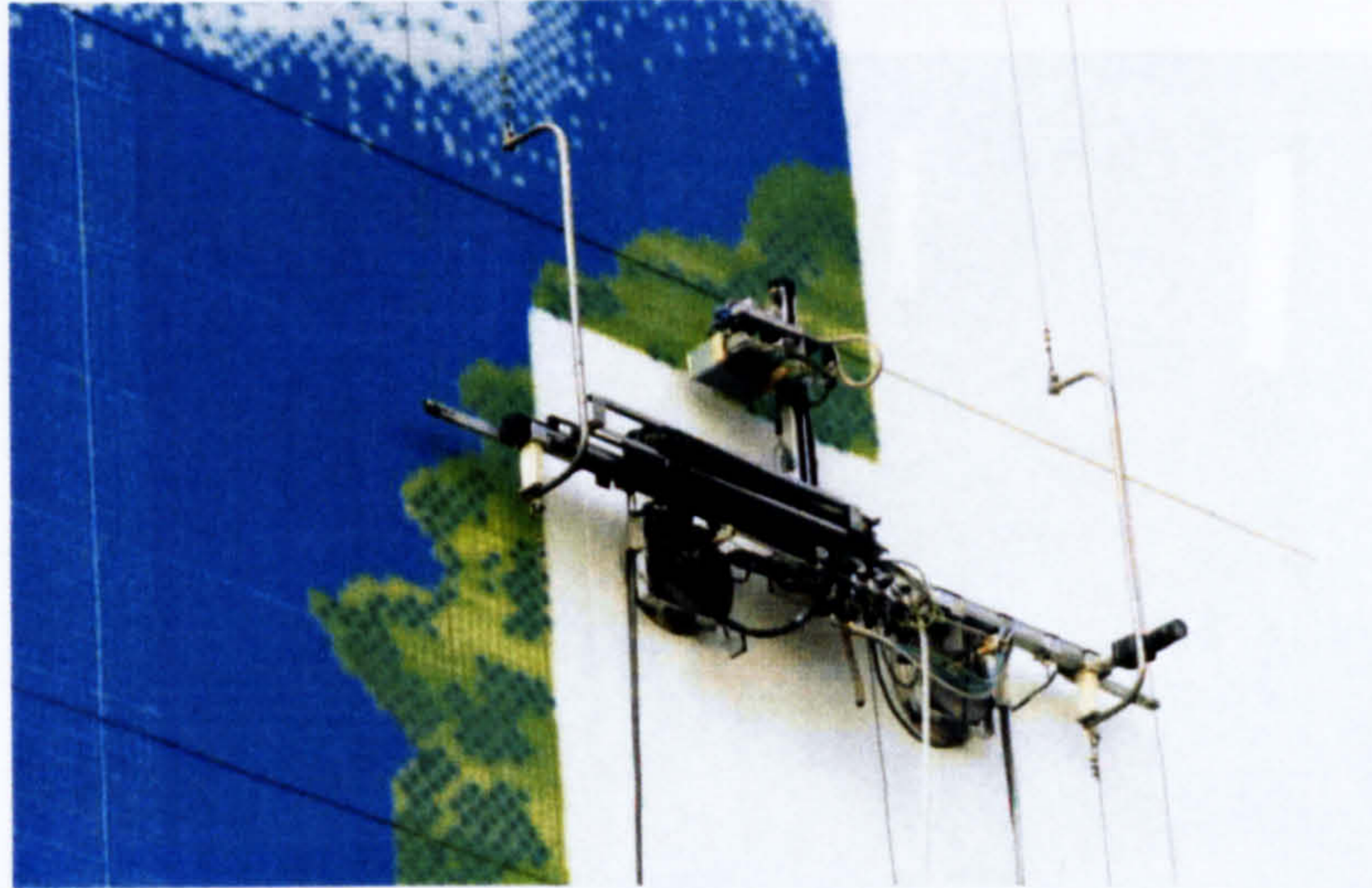


Figure 3.24: Automated exterior wall-surface paint application system
Courtesy: Tokyu Construction Co. Ltd.

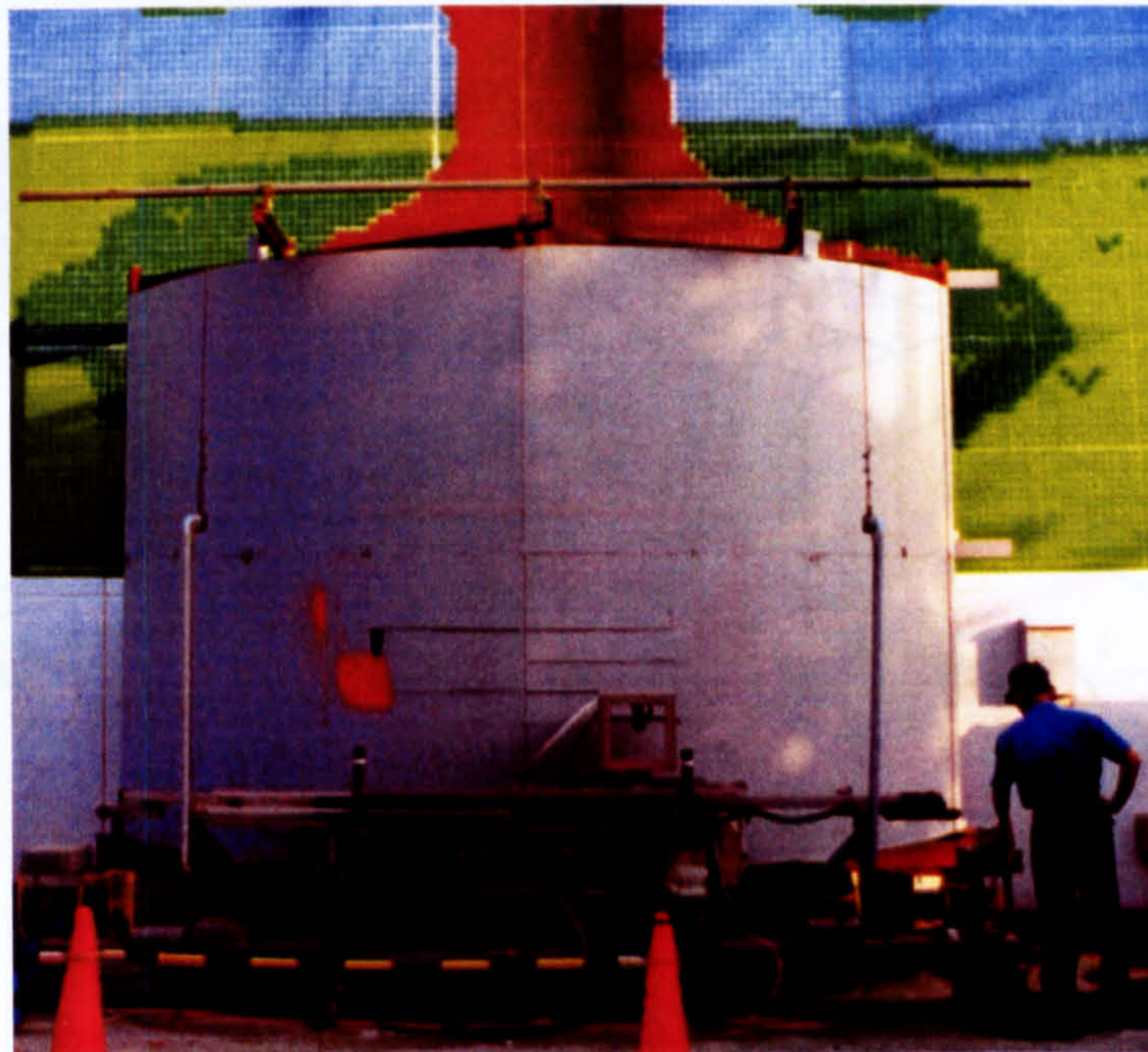


Figure 3.25: Automated silo surface paint application system
Courtesy: Tokyu Construction Co. Ltd.



Figure 3.26: BRONCO, automated masonry construction system
Courtesy: University of Stuttgart, ISW

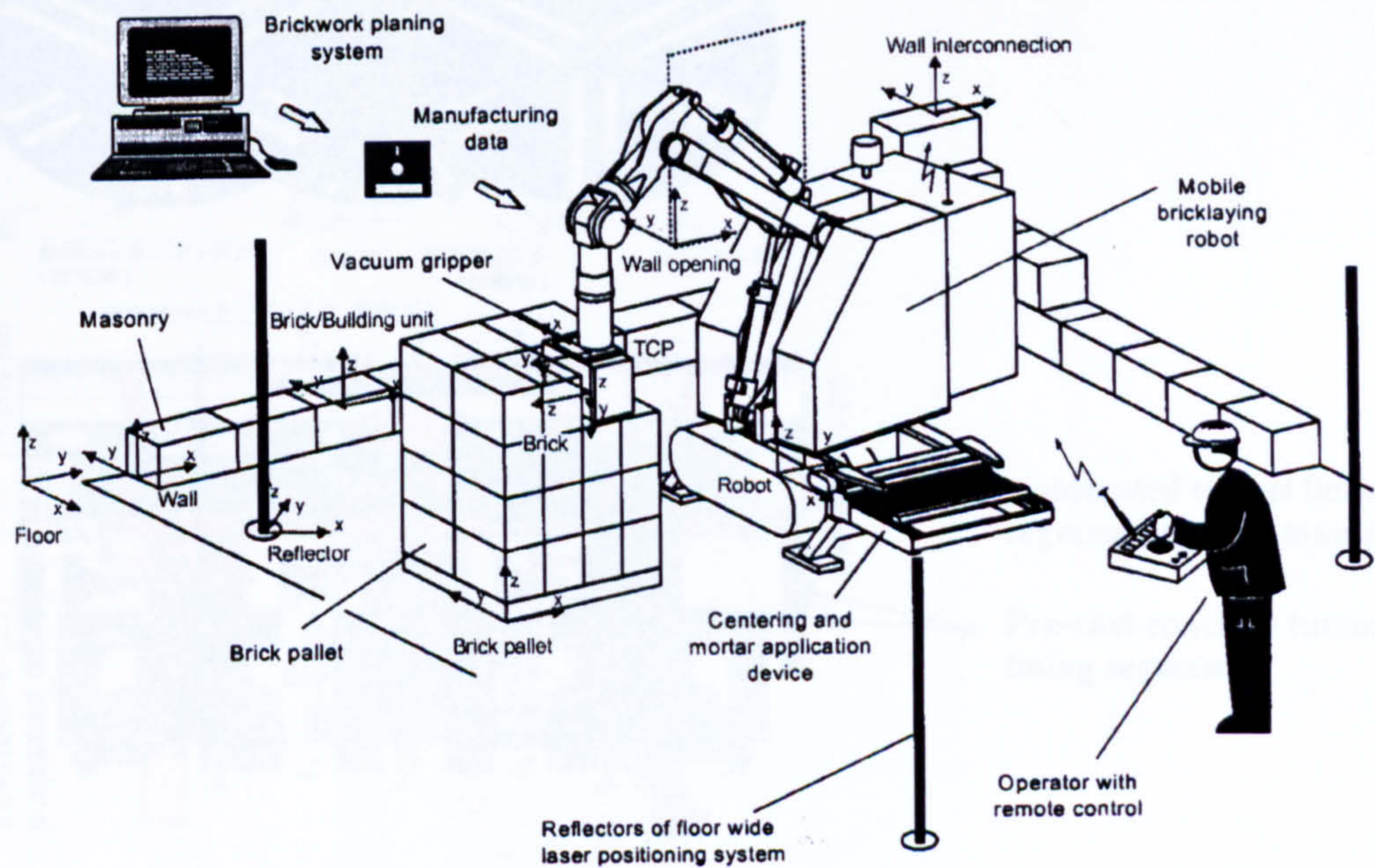


Figure 3.27: BRONCO geometric work station relationships
Source: Pritschow *et al* 1998



Figure 3.28: Tele-operated excavation system
Courtesy: Tokyu Construction Co. Ltd.

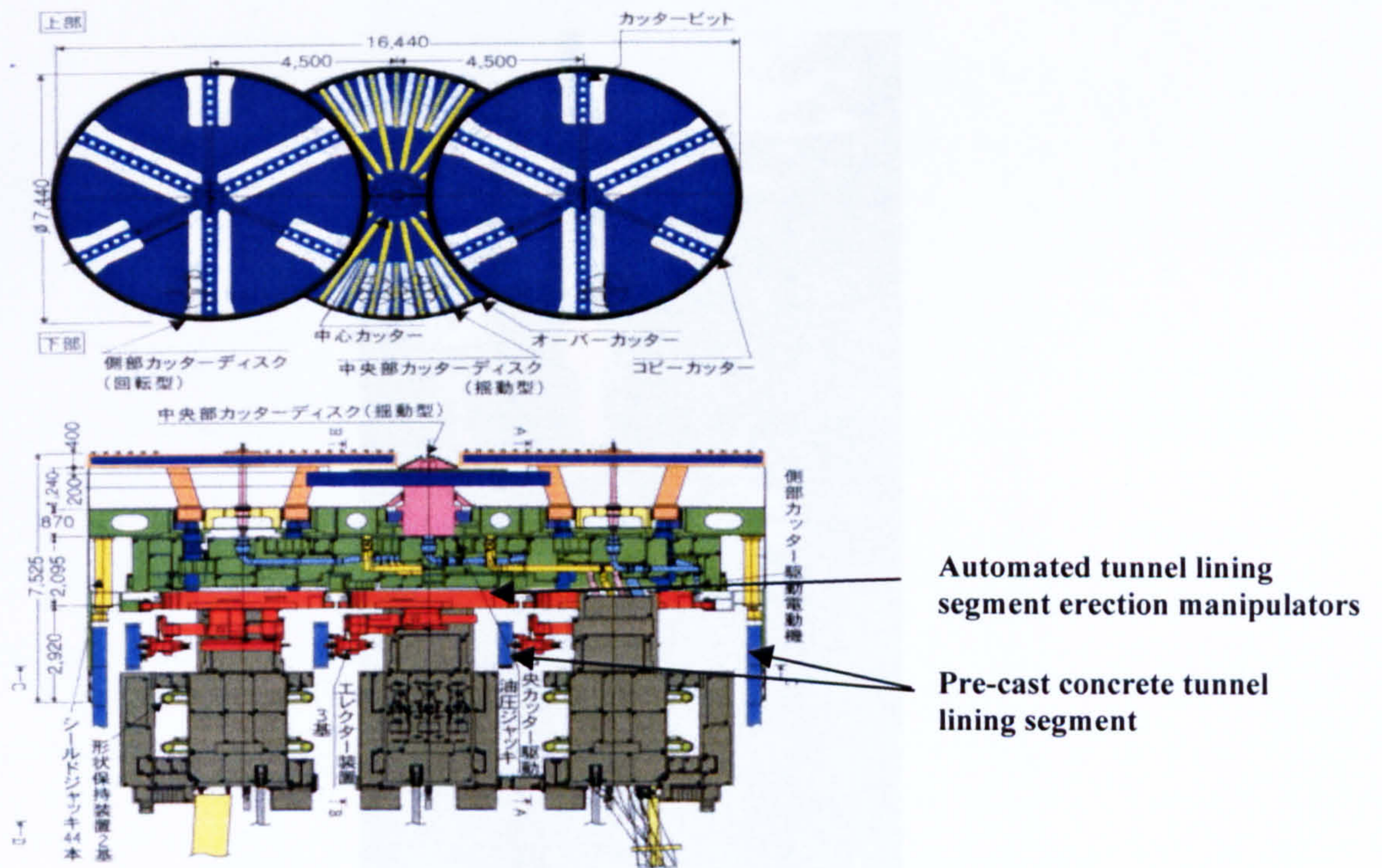


Figure 3.29: Triple-faced TBM with automated segment manipulators
Courtesy: Kumagai Gumi Co. Ltd.

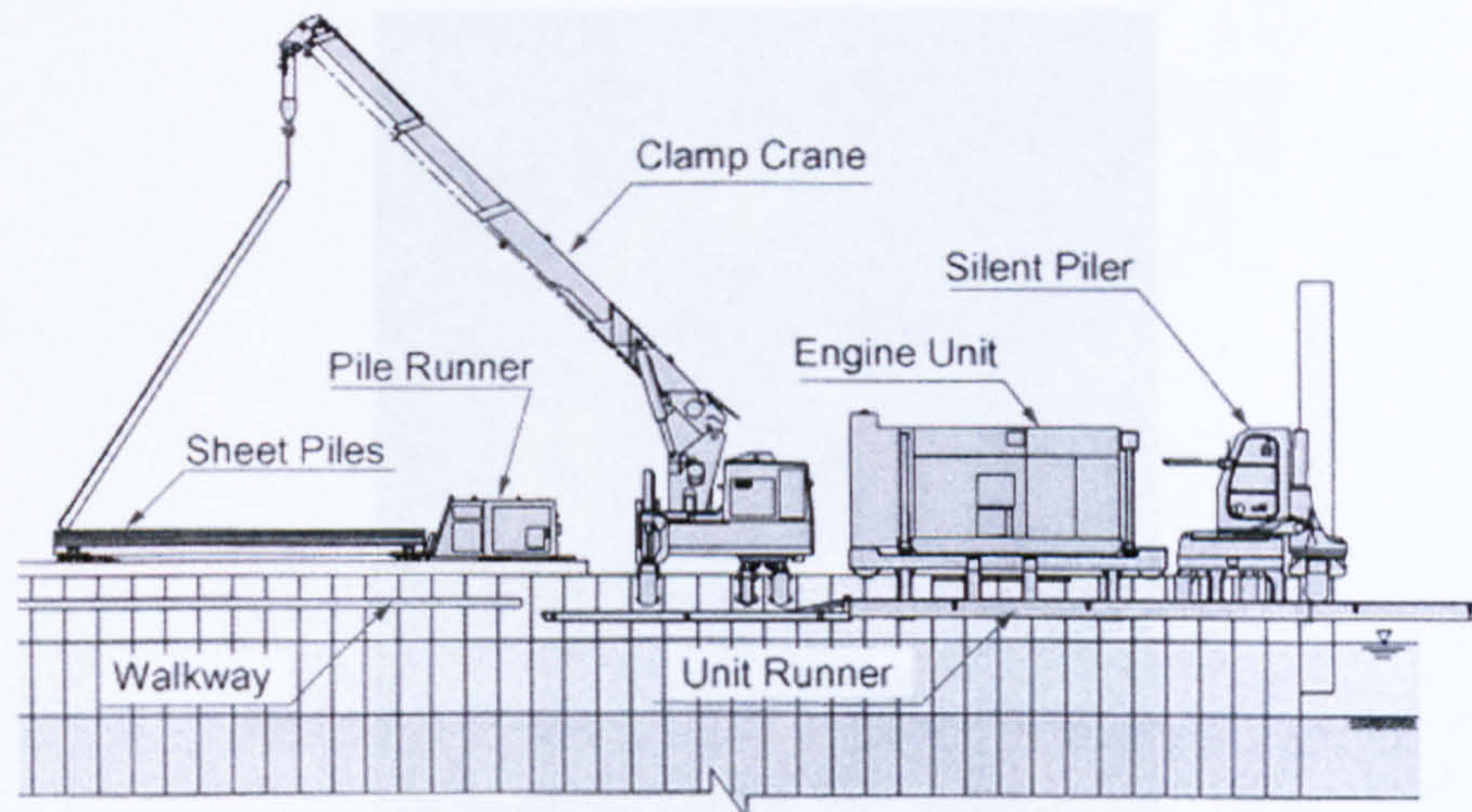


Figure 3.30: Automatic pile installation system configuration
Courtesy: Giken Seisakusho Co. Ltd



Figure 3.31: Automatic pile installation system
Courtesy: Giken Seisakusho Co. Ltd.



Figure 3.32: BROKK BM330 demolition manipulator
Courtesy: BROKK ÅB

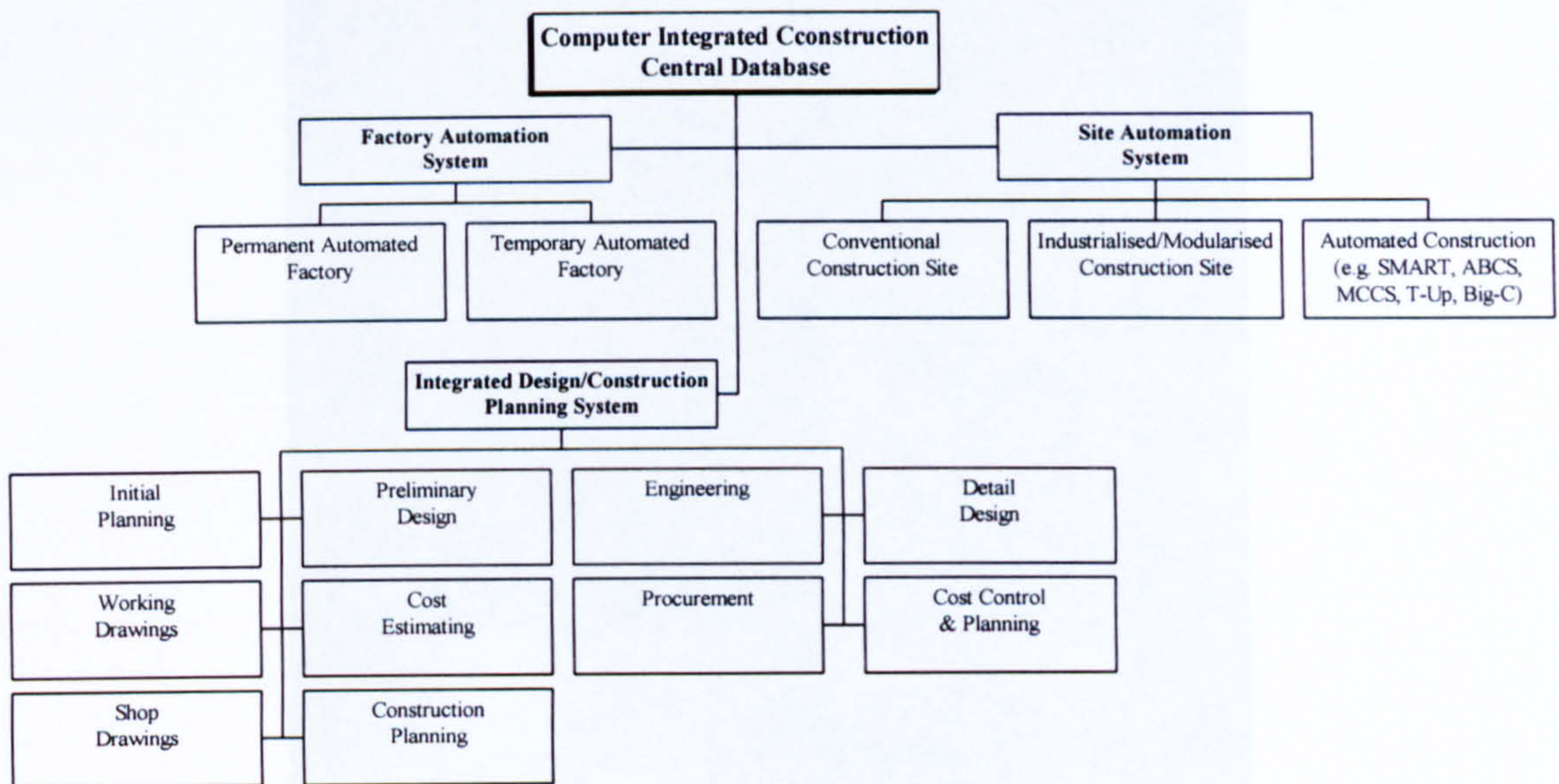


Figure 3.33: Computer-Integrated Construction model
Source: Miyatake & Kangari 1993

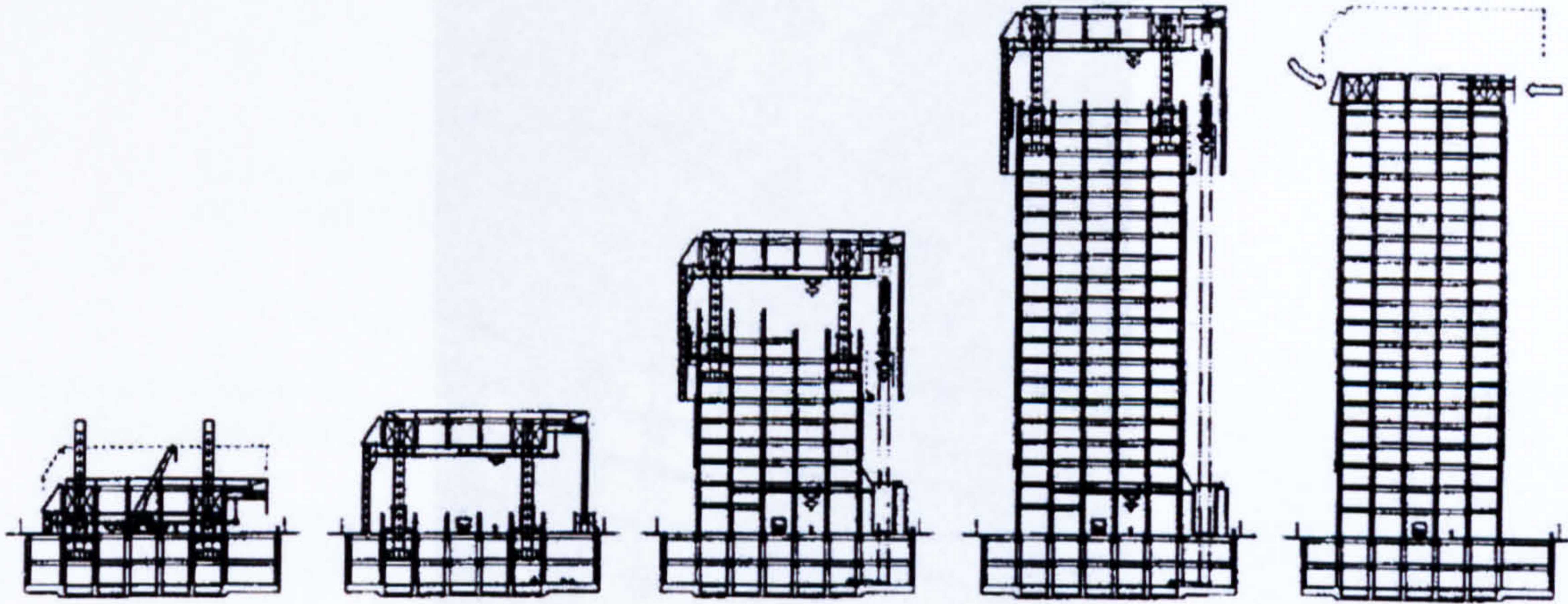


Figure 3.34: SMART system construction procedure
Courtesy: Shimizu Corporation



Figure 3.35: SMART system exterior view, Juroku Bank, Nagoya
Courtesy: Shimizu Corporation

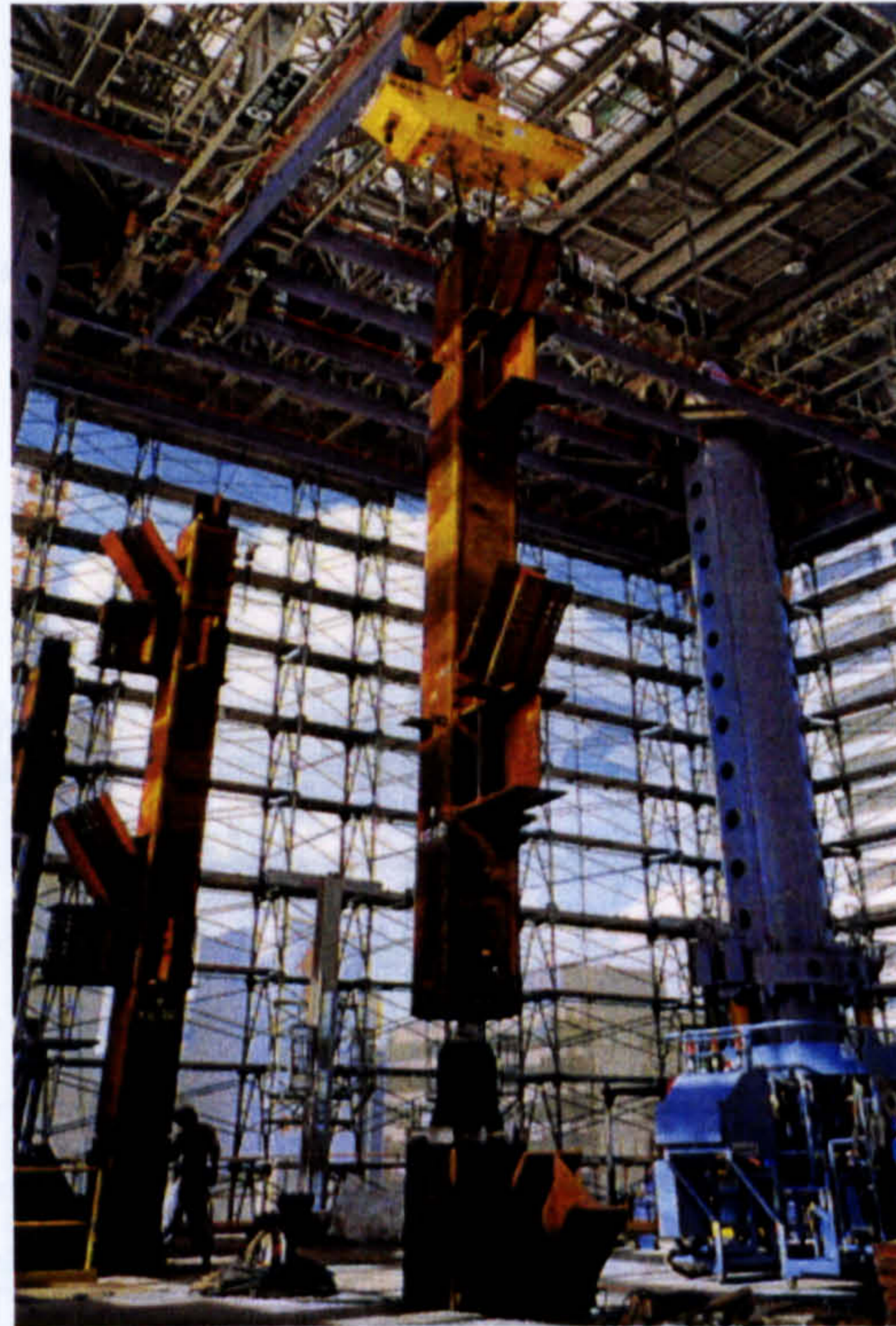


Figure 3.36: SMART system interior view
Courtesy: Shimizu Corporation

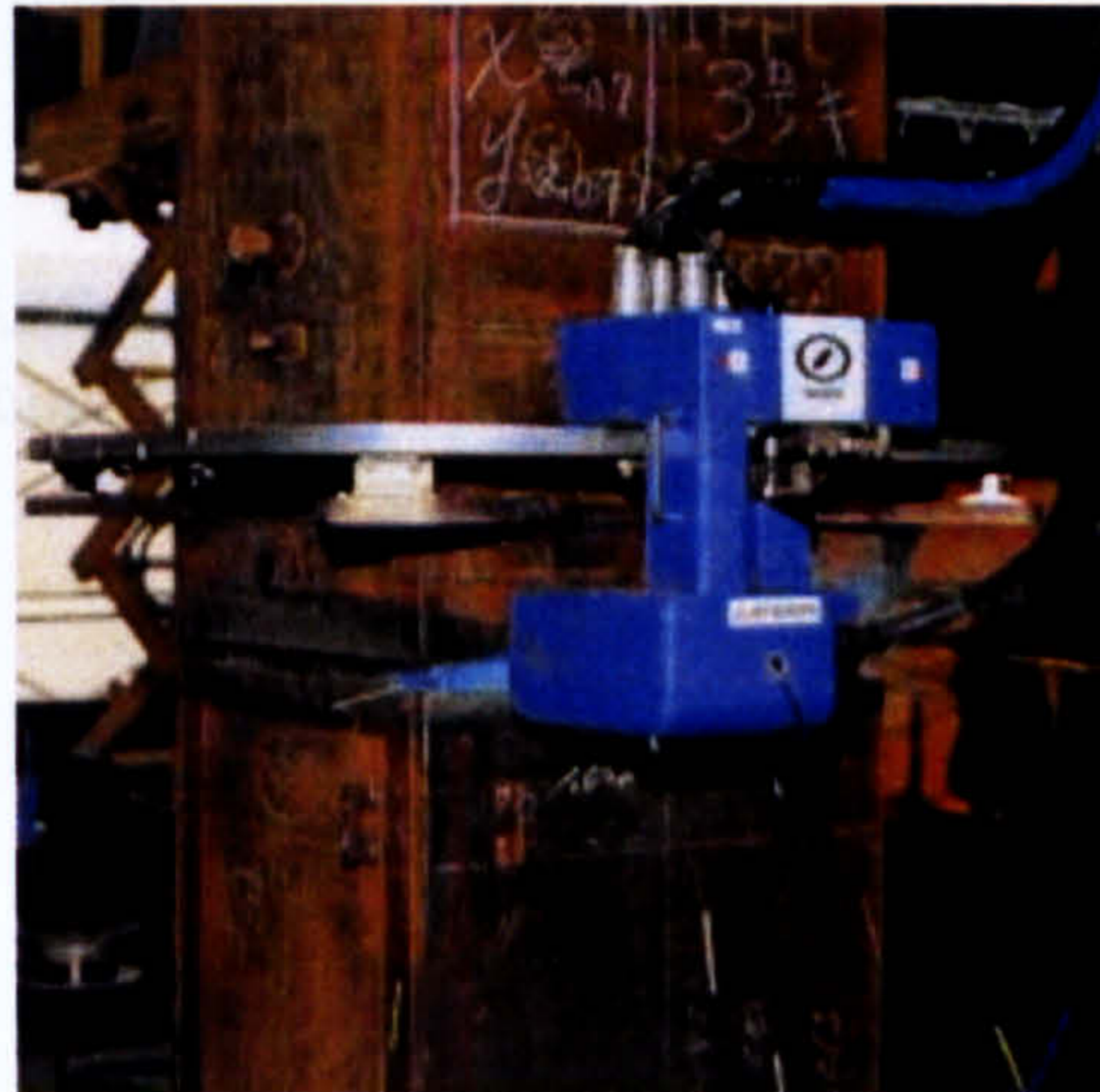


Figure 3.37: SMART system column welding robot
Courtesy: Shimizu Corporation

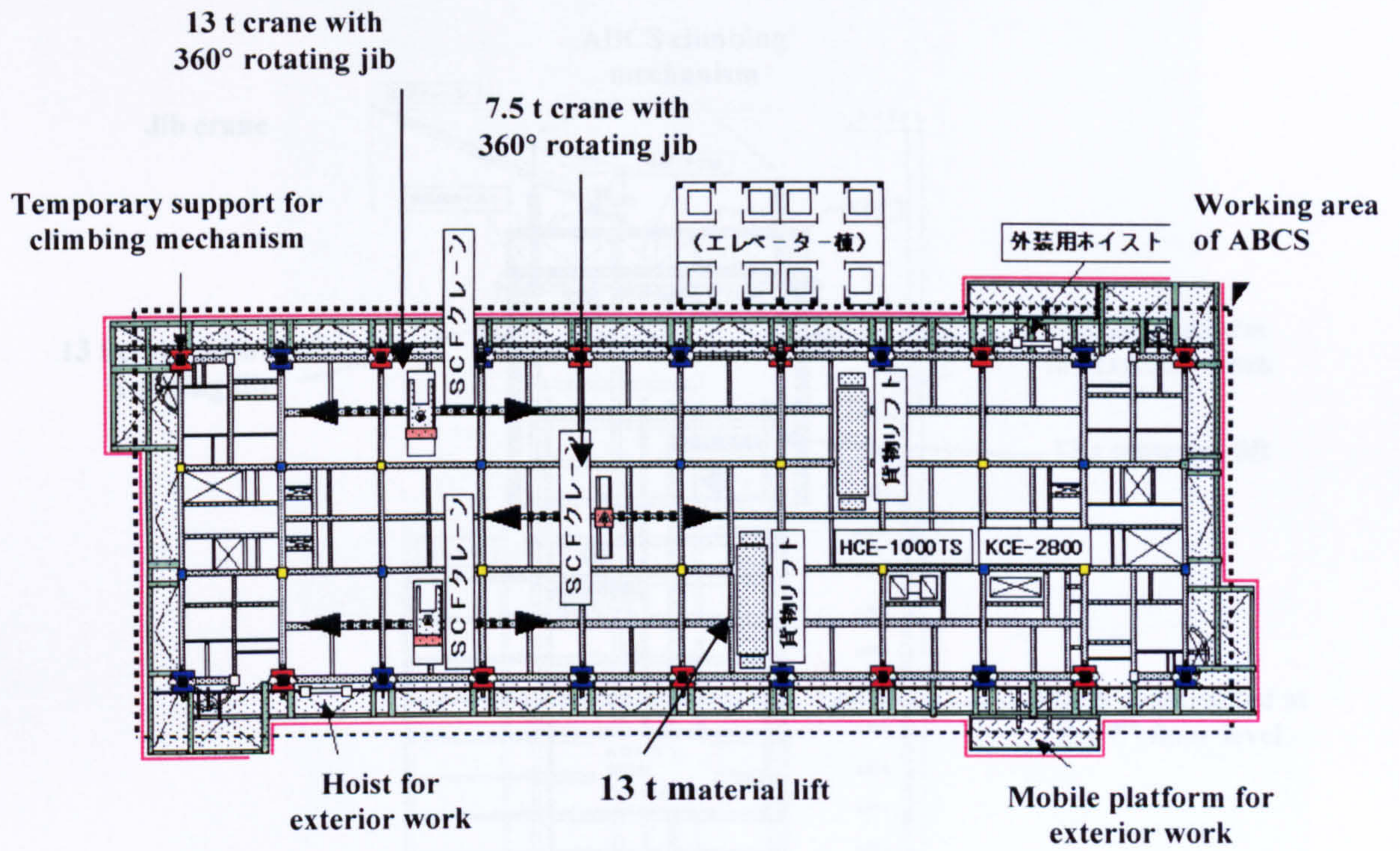


Figure 3.38: Plan of ABCS super-construction factory
Source: adapted from Miyakawa *et al* 2000

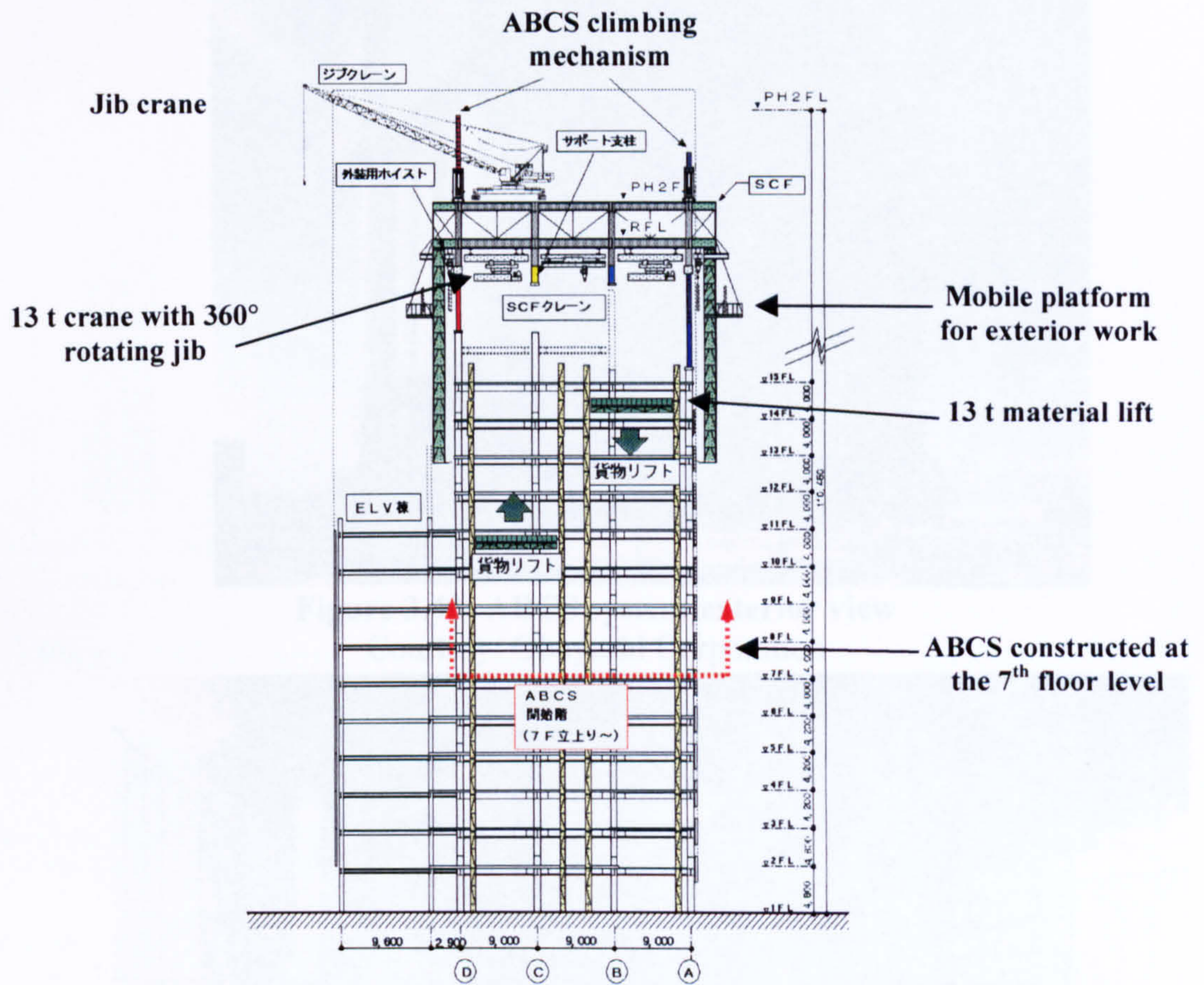


Figure 3.39: Cross section of ABCS super construction factory
Source: adapted from Miyakawa et al 2000

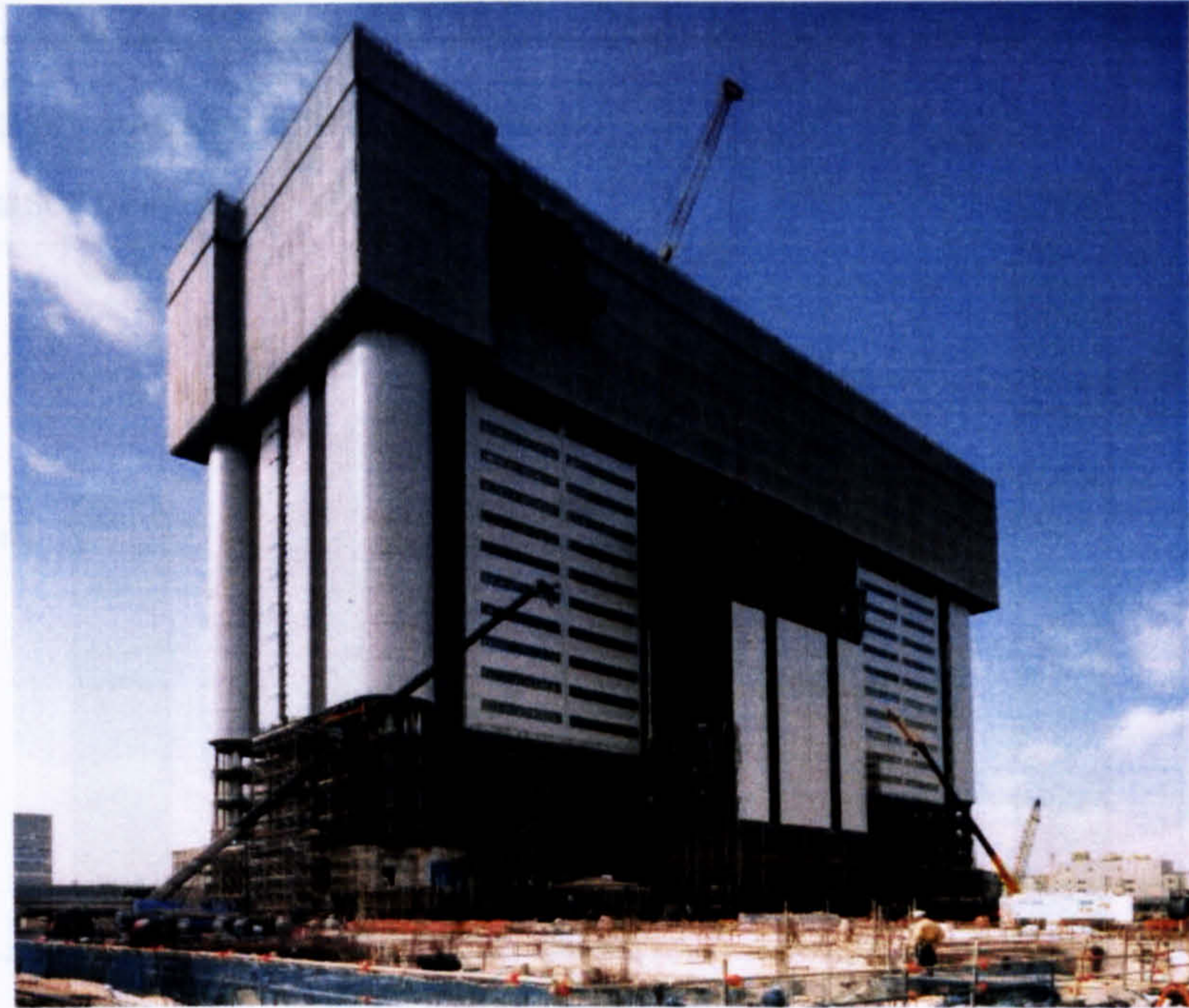


Figure 3.40: ABCS system exterior view
Courtesy: Obayashi Corporation



Figure 3.41: ABCS system interior view
Courtesy: Obayashi Corporation

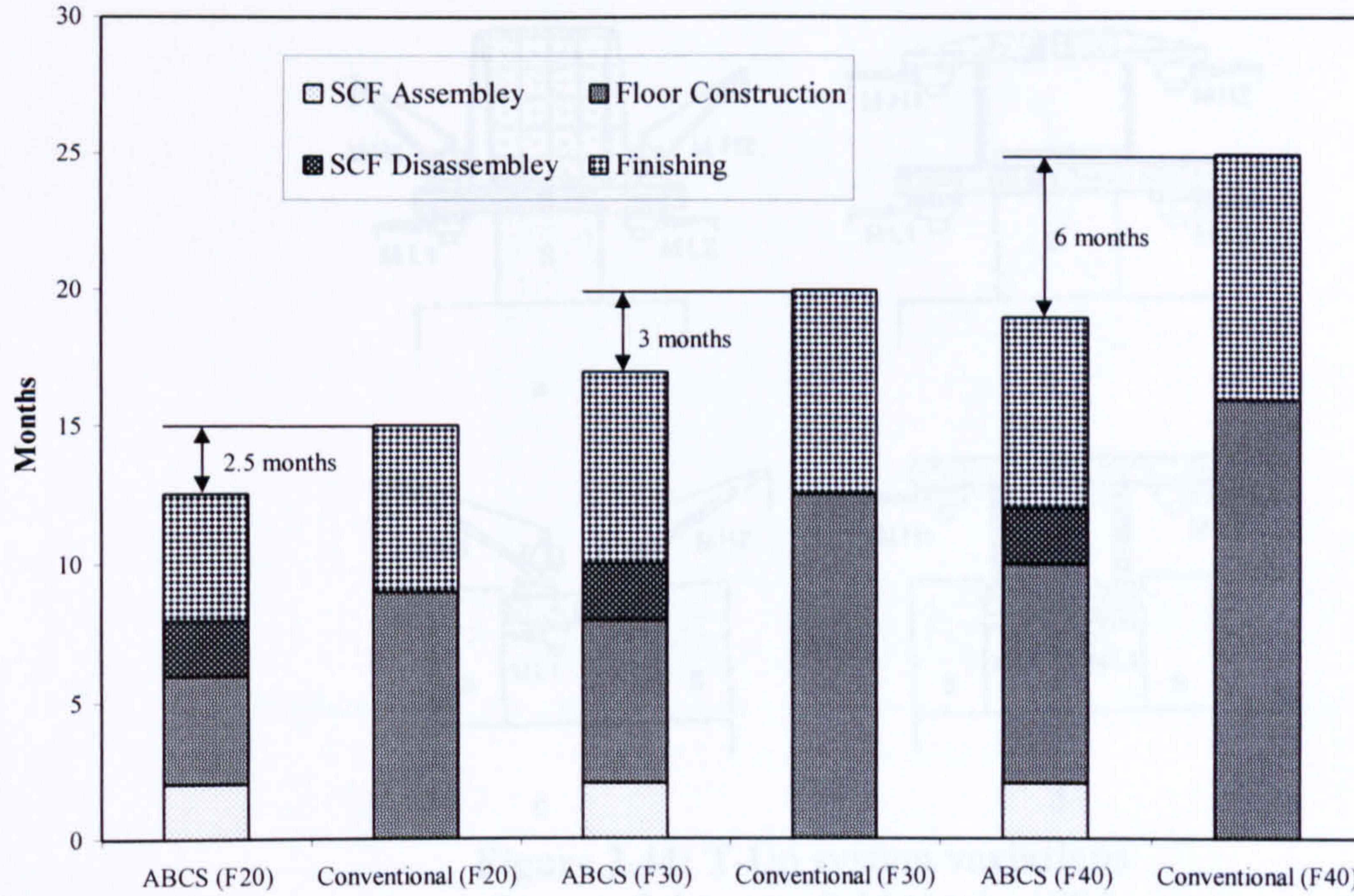


Figure 3.42: Comparison of construction schedules, conventional vs ABCS
Source: adapted from Kudoh 1995

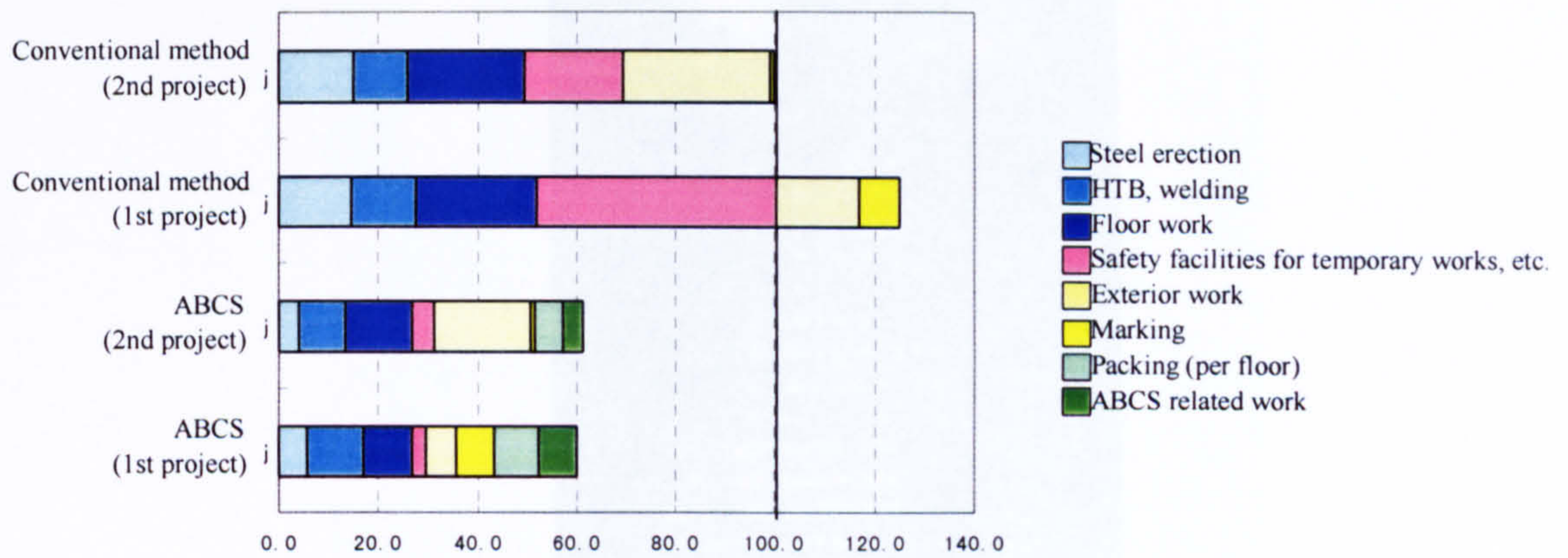


Figure 3.43: Comparison of unit labour requirements, conventional vs ABCS
Source: Miyakawa *et al* 2000

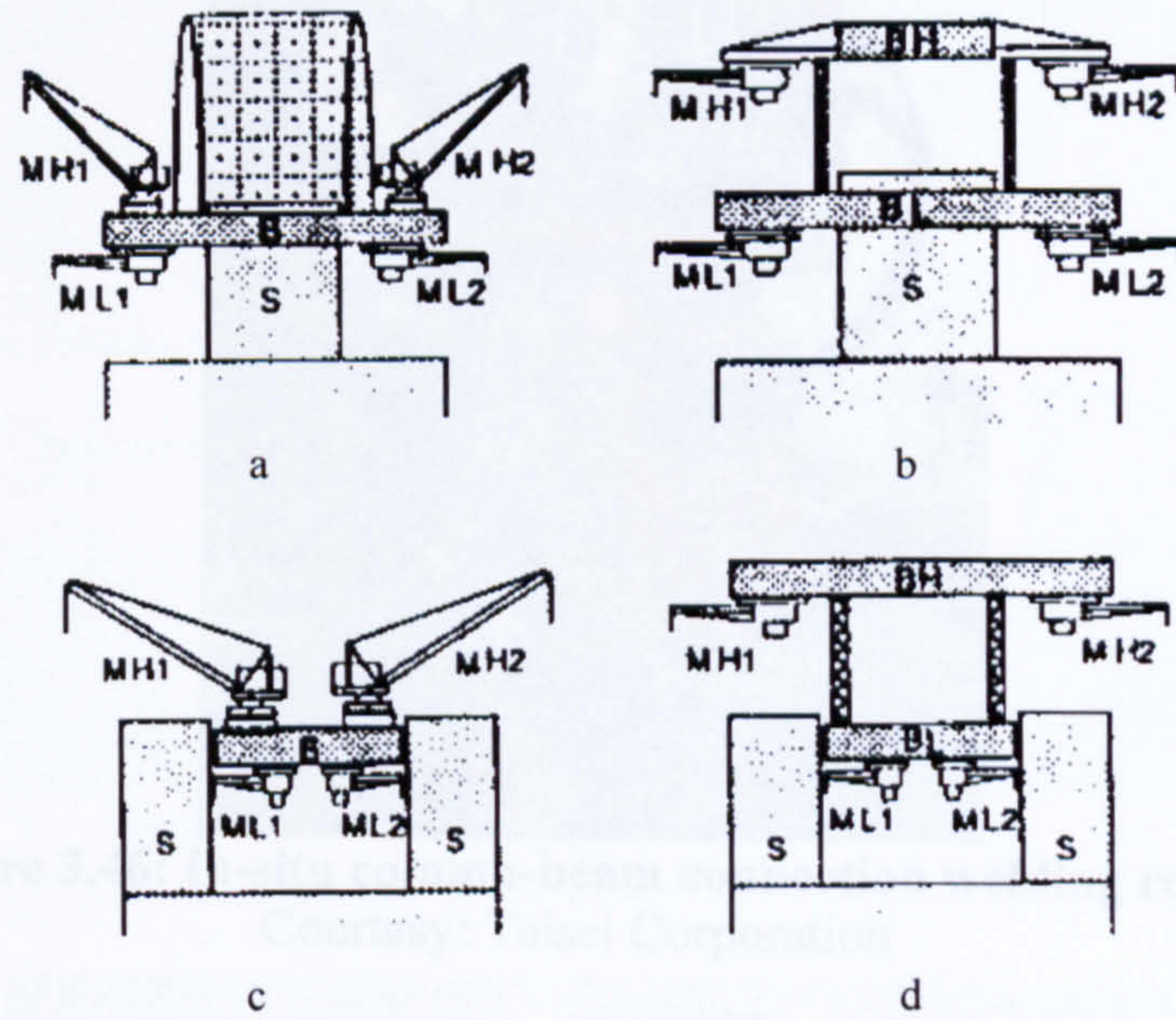


Figure 3.44: T-Up system variations

Source: Sakamoto & Mitsuoka 1994



Figure 3.45: Taisei T-Up system

Courtesy: Taisei Corporation

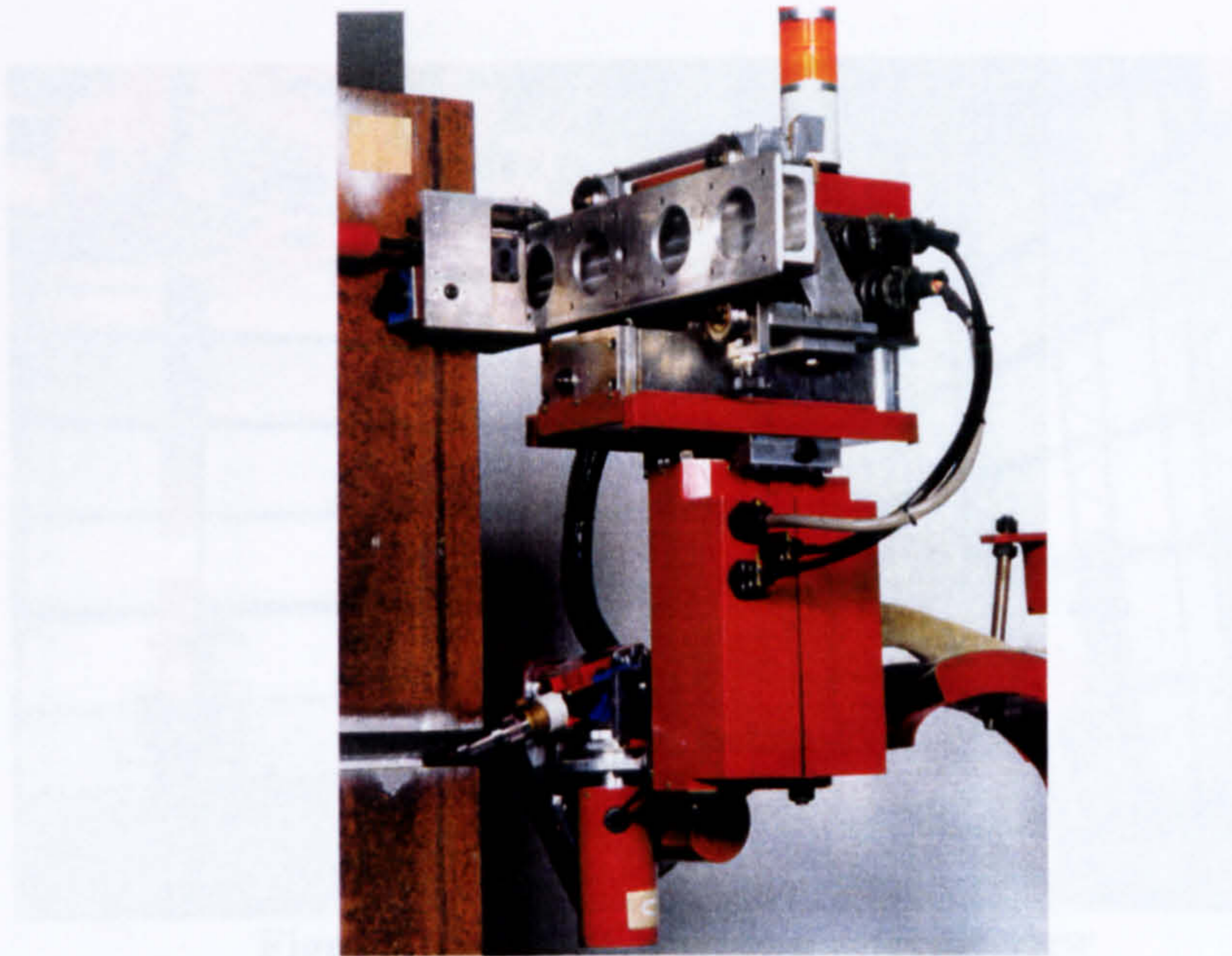


Figure 3.46: In-situ column-beam connection welding robot
Courtesy: Taisei Corporation



Figure 3.47: MCCS system exterior view
Courtesy: Maeda Corporation

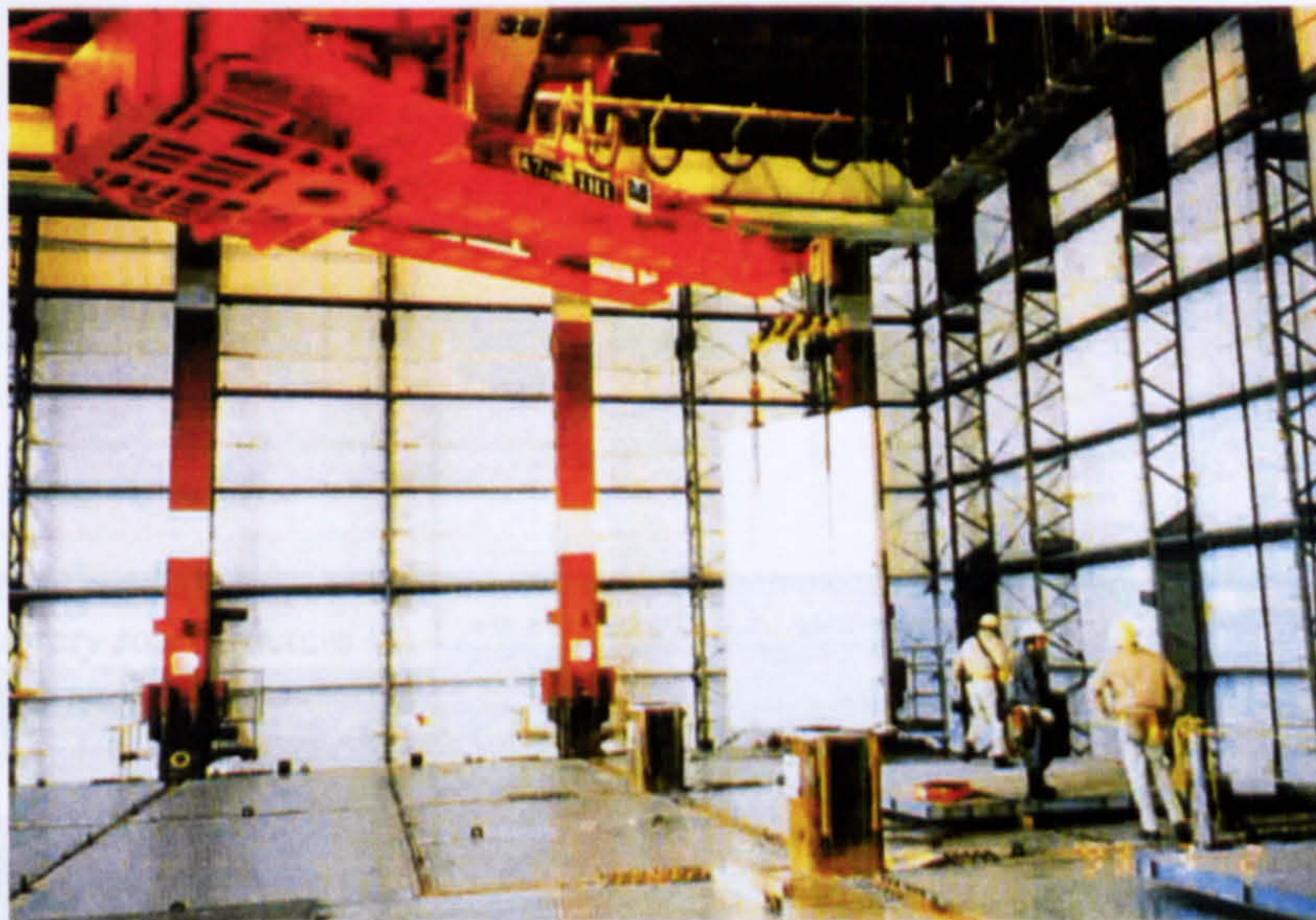


Figure 3.48: MCCS system interior view
Courtesy: Maeda Corporation

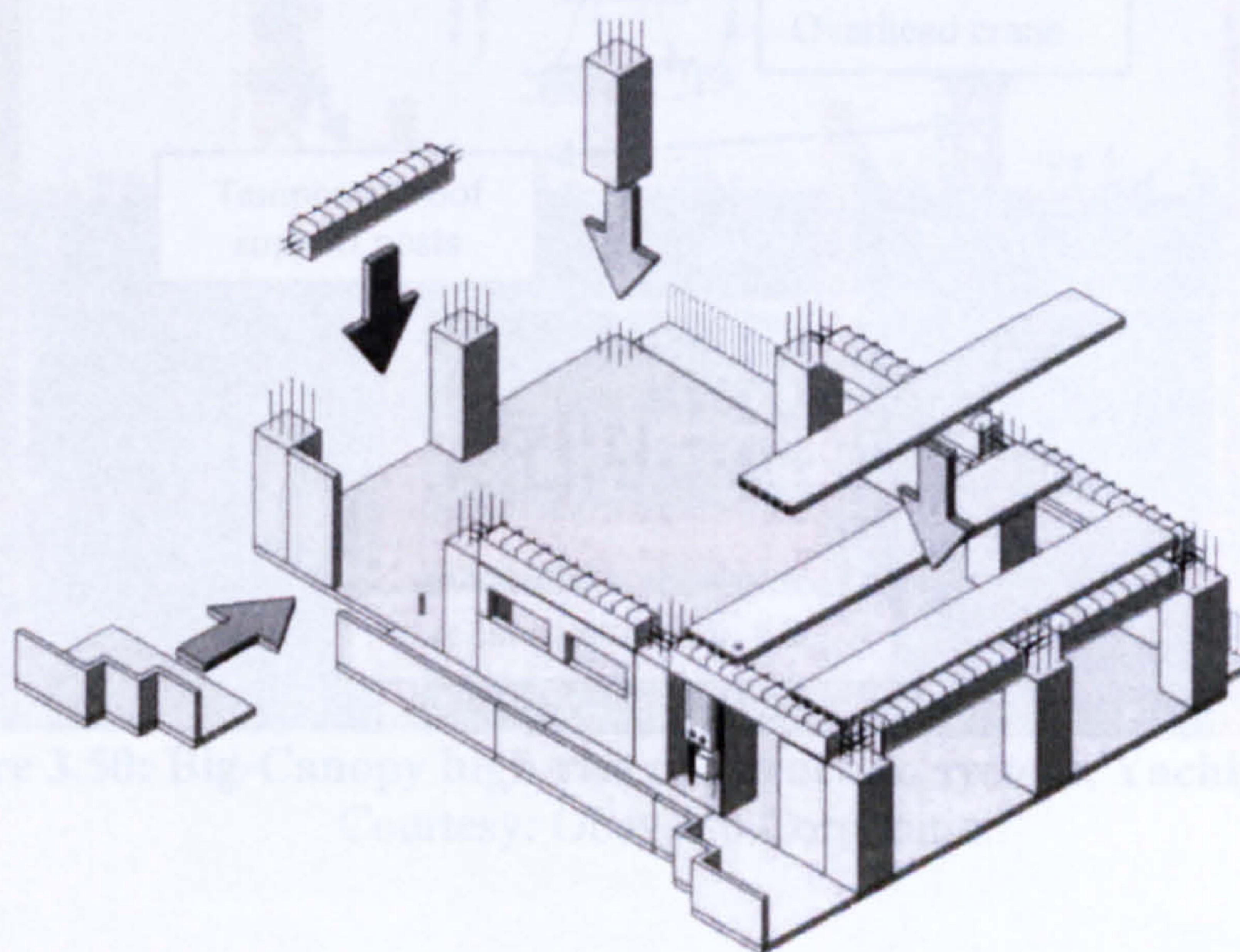


Figure 3.49: Big-Canopy prefabricated sub-assembly construction system
Source: Wakisaka *et al* 2000

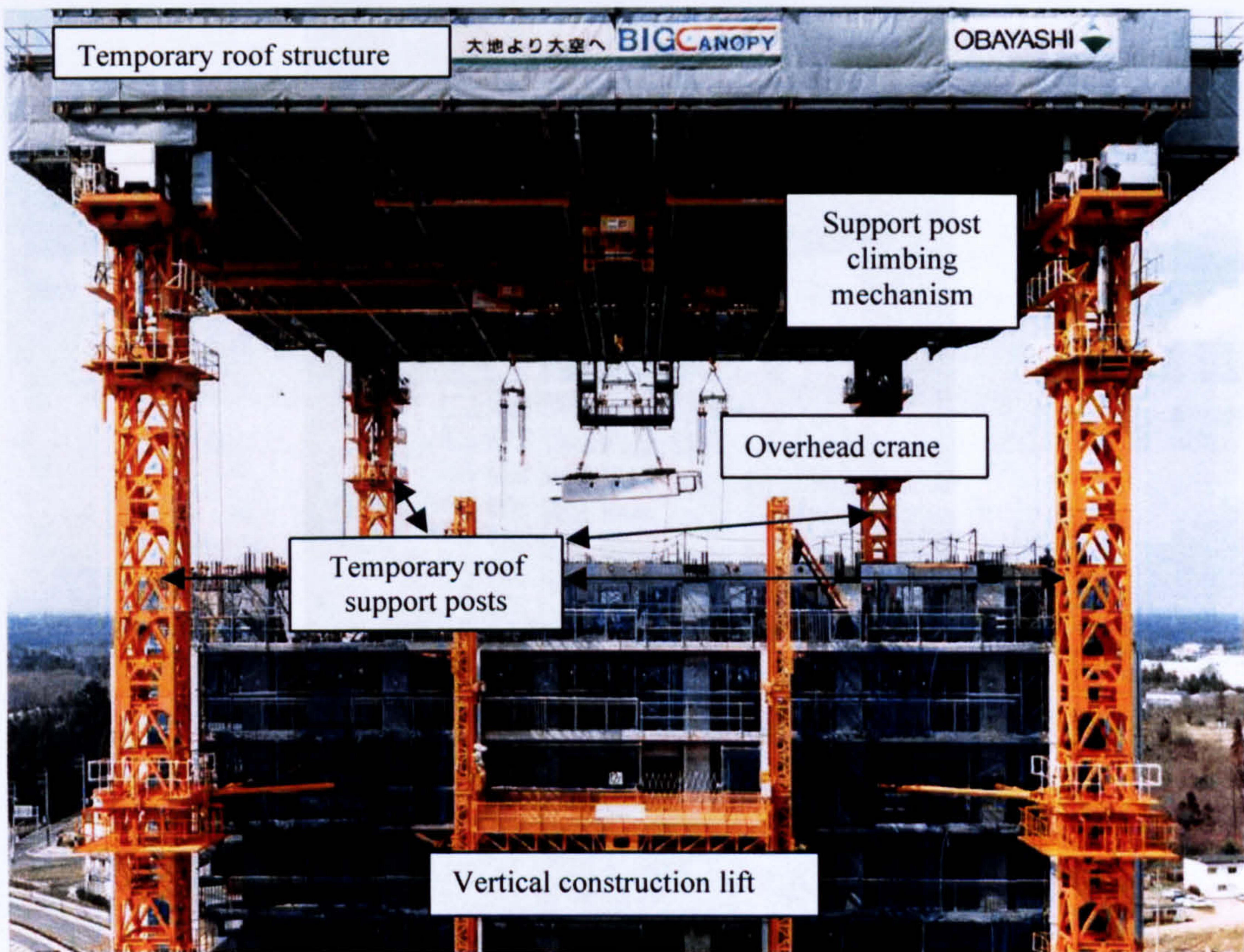


Figure 3.50: Big-Canopy high-rise construction system, Yachiyo project
Courtesy: Obayashi Corporation

Figure 3.51: Big-Canopy high-rise construction system, 1115 Square, Singapore
Courtesy: Obayashi Corporation



Figure 3.51: Big-Canopy high-rise construction system, DBS Square, Singapore
Courtesy: Obayashi Corporation

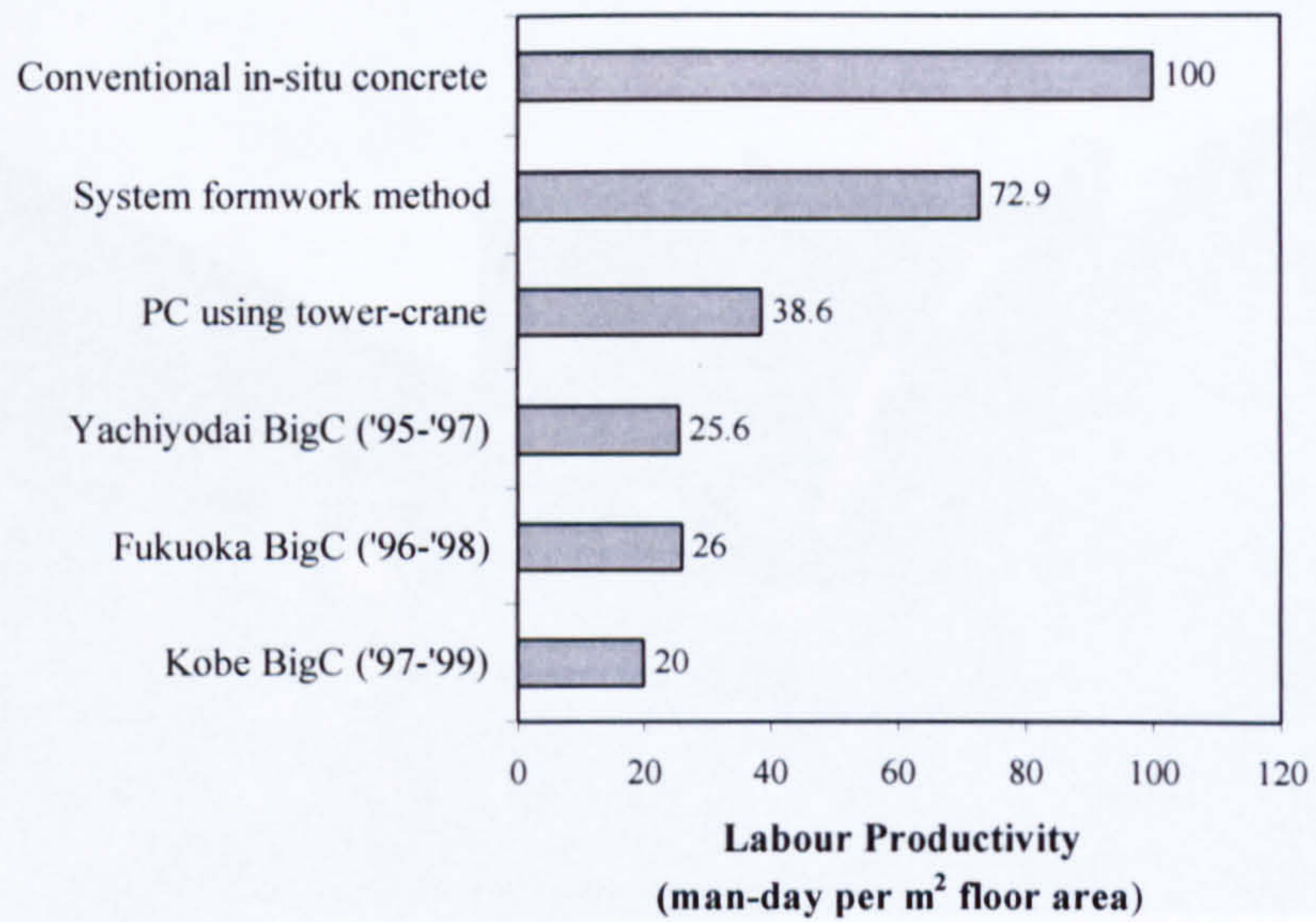


Figure 3.52: Comparison of labour man-day/m² floor area
Source: Furuya *et al* 2000



Figure 3.53: New SMART system, Central Park West Sea Tower project
Courtesy: Shimizu Corporation



Figure 3.54: BROKK BM150, Meadowside Granary demolition project
Courtesy: Corecut Ltd & Scotdem Ltd

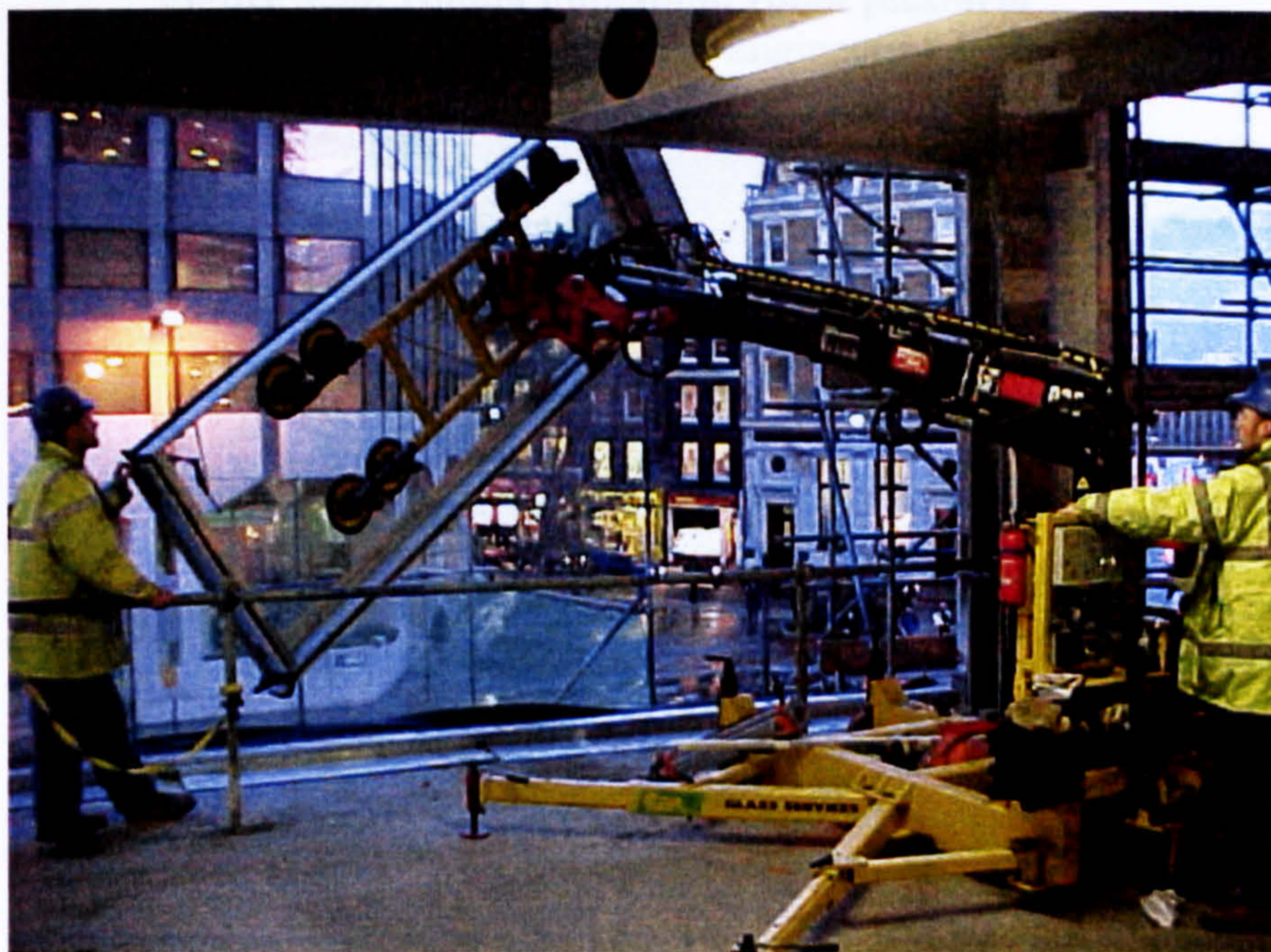


Figure 3.55: Ergonomic glazing manipulator unit
Courtesy: GGR Glass Services Ltd & SN Murdoch Ltd

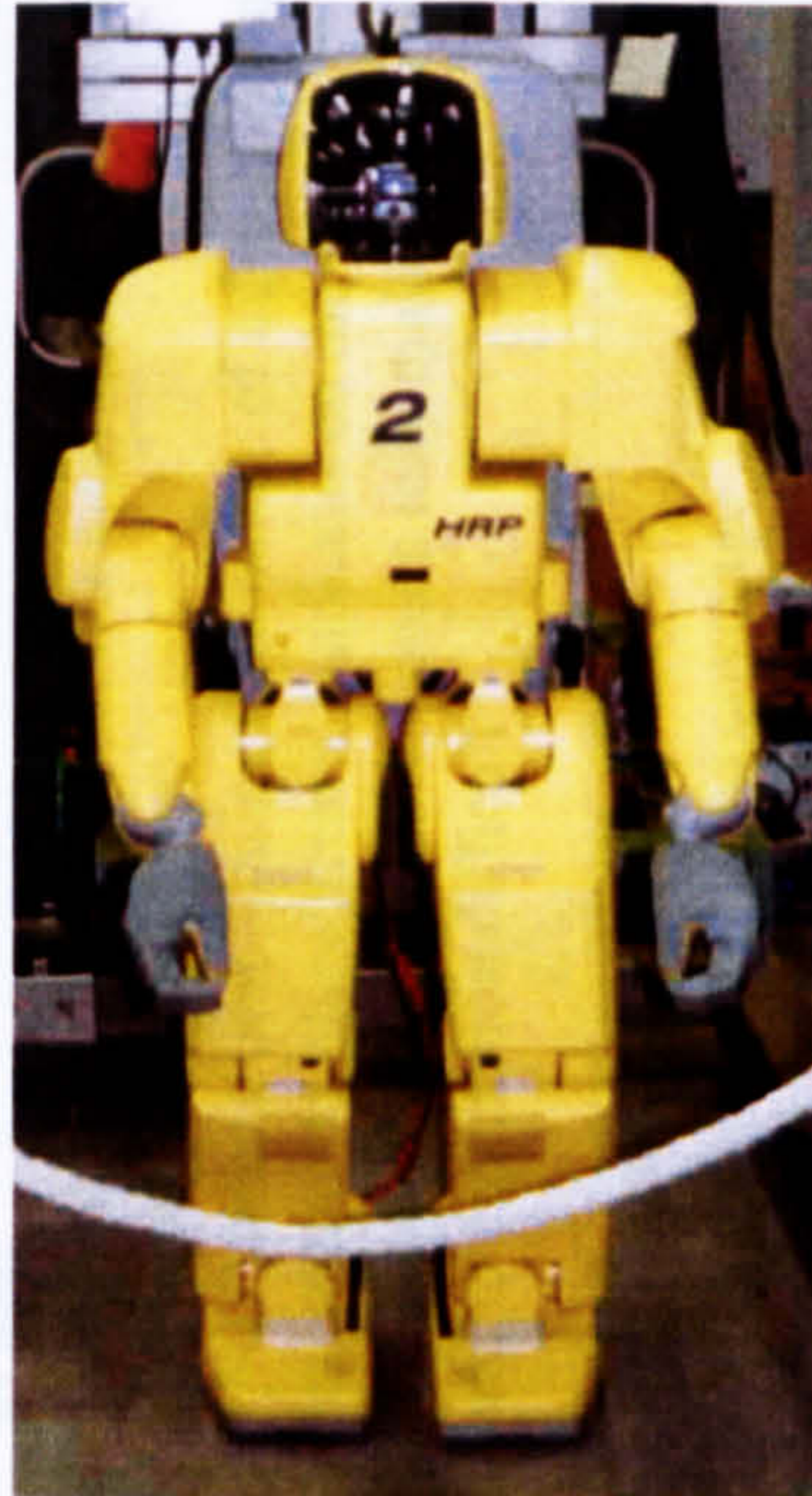


Figure 3.56: Honda humanoid robot platform
Courtesy: Japanese MITI Mechanical Engineering Laboratory

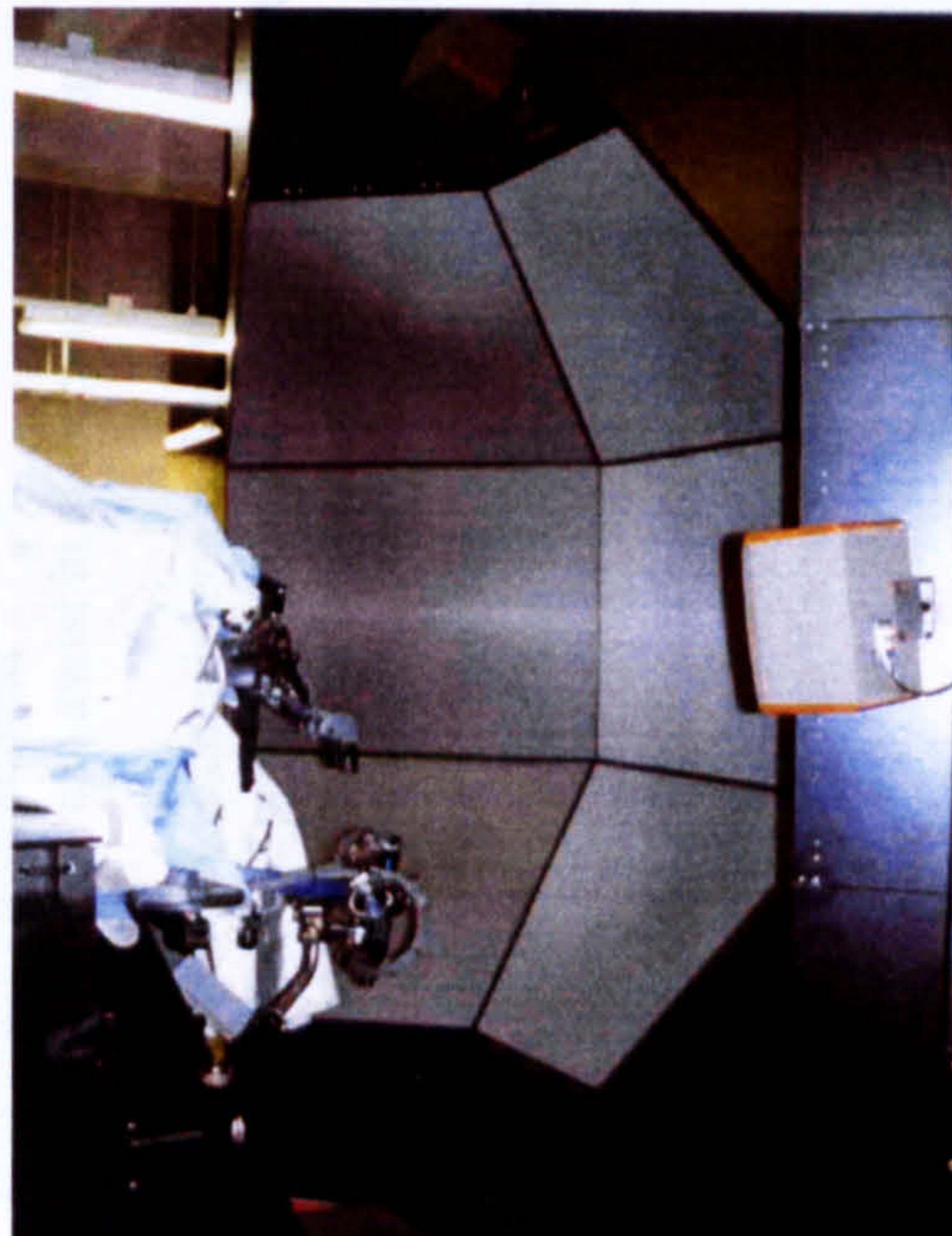


Figure 3.57: Spatially correspondent humanoid platform control system
Courtesy: Japanese MITI Mechanical Engineering Laboratory

Source of evidence	Strengths	Weaknesses
Documentation	<ul style="list-style-type: none"> • stable - can be reviewed repeatedly • unobtrusive – not created as the result of a case study • exact – contains exact details • broad coverage of events in time 	<ul style="list-style-type: none"> • can be difficult to retrieve • biased selectively if collection is incomplete • reporting bias – reflects unknown bias of author • access – may be deliberately blocked
Group or individual interviews	<ul style="list-style-type: none"> • targeted – selection of participants based upon the topics and needs of the study • insightful – provides a rich body of data in the respondents own context • communication – can assist in overcoming language barriers • interaction – researcher interacts directly with respondents and provides opportunity for clarification, probing and non-scripted follow-up questions • subject – if a small number of participants are used, there is opportunity for complex subjects. • quantity – allows collection from a group of people much more quickly 	<ul style="list-style-type: none"> • danger of bias if questions are poorly constructed and moderated • response bias – may not be a random sample • risk of inaccuracies if participants have poor recall • reflexivity – the participants tell the moderator what they want to hear • group interaction – responses of individuals may not be independent of the group • “live” interaction – immediate nature of interaction may lead researcher to place greater emphasis on the results • open-ended – nature of responses may make summarisation and interpretation difficult
Observations	<ul style="list-style-type: none"> • reality – covers events in real time • contextual – covers the context of the event • emic – data presented in it’s indigenous form 	<ul style="list-style-type: none"> • time – consuming • selectivity – unless broad coverage • reflexivity – the observed process may be undertaken differently due to the presence of the observer • cost – it may be prohibitively expensive to employ a sufficient number of observers
Physical artefacts	<ul style="list-style-type: none"> • insightful into cultural features • insightful into technical operations 	<ul style="list-style-type: none"> • selectivity • availability

Table 3.1: Strengths and weaknesses of qualitative research techniques

Source: Bickman 1998

Benefits	Limitations
<ul style="list-style-type: none"> • Data collected from groups more quickly • Researchers may interact with respondents • Opportunity to clarify and probe responses • Emic data – data collected is indigenous • Synergistic effect of the group results in data which may not have been collected through other techniques • Flexible - used to cover a wide array of topics • Results may present data of additional value to the research • Overcome any language barriers more easily 	<ul style="list-style-type: none"> • Groupthink – nonconformists suppress disagreeing opinions • Small number of respondents limits generalisations to larger populations • Responses may be dominated by one prominent individual • Live nature of interaction with respondents may lead to greater faith being placed in the findings • Open-ended nature of responses makes summarisation and interpretation complex • Unskilled or inexperienced moderator may unknowingly bias results or provide cues as to what type of response is required.

Table 3.2: Benefits and limitations of focus group interviews

Source: Bickman & Rog 1998; Denscombe 1998; Morgan 1997; Morgan 1998a

Company	No. of Participants	Location
Ministry of Construction, Public Works Research Institute	5	Tsukuba Science City, Ibaraki-ken, Japan
Ministry of International Trade and Industry, Mechanical Engineering Laboratory	3	Tsukuba Science City, Ibaraki-ken, Japan
Obayashi Corporation	5	Technical Research Institute, Kiyose-shi, Tokyo
Tokyu Construction Co. Ltd.	4	Institute of Technology, Shibuya-ku, Tokyo
Taisei Corporation	4	Taisei Research Institute, Totsuka-ku, Yokohama
Takanaka Corporation	2	Takanaka Research & Development Institute, Ohtsuka, Inzai, Chiba
Shimizu Corporation	2	Head Office, Seavans South, Minato-ku, Tokyo
Maeda Corporation	3	Head office, Chiyoda-ku, Tokyo, Japan
Kajima Corporation & Takahashi Construction Systems Inc.	4	Maruzenshō warehouse project Phase III, Funabashi-ku, Tokyo
Kumagai Gumi Co. Ltd.	7	Hanzomon No.11 Subway Project, Tokyo

Table 3.3: Summary of focus group participants and meeting locations

Designation	Number of Participants
President	1
Director	2
General Manager-in-charge	1
General Manager	7
Deputy General Manager	4
Divisional Manager	4
Chief Research Engineer	1
Deputy Chief Research Engineer	2
Chief Mechanical Engineer	1
Senior Research Engineer	6
Research Engineer	7
Technical Advisor	1
Project Manager	2
<i>TOTAL</i>	<i>39</i>

Table 3.4: Designation of focus group participants

Research Question	Hypothesis	Sample	Concept/Construct	Operational Definition
1. Within Japanese construction companies, what academic and professional qualifications to those concerned with automation and robotics research hold?	<i>Hypothesis One</i> Japanese contractors continue to employ a high percentage of mechanical and electrical engineers, which conduct in-house automation and robotics research and development.	A purposive sample of Japanese general construction contractors (Big-six by annual sales)	Concept: qualifications of existing employees. Construct: academic qualifications of company employee's and focus group participants.	Focus groups: question regarding the academic qualifications of research staff and focus group participant's (Q1).
2. To what extent do Japanese contractors continue to invest in construction automation research, development and deployment?	<i>Hypothesis Two</i> Japanese contractors continue to contribute substantial investment towards the research and development of construction automation and robotics.	A purposive sample of Japanese general construction contractors (Big-six by annual sales)	Concept: trend in construction automation R&D expenditure. Construct: general R&D expenditure, construction automation R&D expenditure.	Focus groups: question concerning technology strategies and R&D investment. Factual information obtained from focus groups and annual reports (Q3).
3. To what extent are tangible and intangible benefits drivers for the research and development of Japanese construction automation and robotics?	<i>Hypothesis Three</i> Japanese contractors place greater emphasis upon the intangible benefits of construction automation and are more concerned with strategic, rather than, short term advantages and benefits.	A purposive sample of Japanese general construction contractors (Big-six by annual sales)	Concept: what are the main drivers for Japanese contractors research and development objectives Construct: specific reasons for contractors ongoing research and development	Focus groups: question concerning the extent which intangible and tangible benefits are driving research and development. Open questions eliciting research engineer's opinions (Q4 & Q5).

Table 3.5: Focus group research questions, hypotheses, sample frames, concepts, constructs and operational definitions

Research Question	Hypothesis	Sample	Concept/Construct	Operational Definition
4. What procedures are adopted in the testing, evaluation and deployment of automation and robotics technologies.	<i>Hypothesis Four</i> Automated technology is extensively tested within laboratory conditions prior to on-site implementation projects.	A purposive sample of Japanese general contractors (Big-six by annual sales)	Concept: what are the development stages for innovative prototype technologies. Construct: specific details of developmental stages of existing applied and prototype technologies.	Focus groups: question concerning the procedure for the development of a prototype technology (Q6).
5. Are existing technologies providing the efficiencies perceived in the early development of construction automation technology?	<i>Hypothesis Five</i> Automation and robotics is providing Japanese contractors with the originally perceived efficiencies relating to construction productivity, labour costs and increased operational safety.	A purposive sample of Japanese general contractors (Big-six by annual sales)	Concept: level of successful efficiency improvements. Construct: benchmarking of automated construction operations to traditional techniques, details of failures, cost overruns and industrial accidents.	Focus groups: question concerning productivity, quality improvements and implementation failures in comparison with traditional construction operations. Factual information obtained from focus groups (Q7 & Q8)
6. To what extent does construction automation require adjustments to the design and construction of structures.	<i>Hypothesis Six</i> Japanese construction projects are being re-engineered to accommodate automation and robotics.	A purposive sample of Japanese general contractors (Big-six by annual sales)	Concept: what adjustments must be made to traditional project organisational structures to accommodate automation and robotics. Construct: specific details of organisational adaptation prior to the introduction of automation and robotics.	Focus groups: question concerning the managerial and organisational changes required to assist the implementation of innovative technologies. Open ended question asking to describe the complementary changes (Q9).

Table 3.5 (cont.): Focus group research questions, hypotheses, sample frames, concepts, constructs and operational definitions

Research Question	Hypothesis	Sample	Concept/Construct	Operational Definition
7. To what extent is automation and robotics technology being utilised within the domestic Japanese construction industry?	<i>Hypothesis Seven</i> on automation and robotics is extensively utilised throughout domestic Japanese construction projects.	A purposive sample of Japanese general construction contractors (Big-six by annual sales)	Concept: deployment of existing technology. Construct: machine description and specification, project details and reasons for implementation	Focus groups: question regarding current deployment of automated construction technology. Factual information obtained from focus groups (Q10).
8. Does existing automated construction technology require greater maintenance and operating expertise when compared to traditional construction plant and machinery?	<i>Hypothesis Eight</i> Existing construction automation and robotics technologies currently employed on Japanese projects require highly skilled operators and maintenance personnel.	A purposive sample of Japanese general construction contractors (Big-six by annual sales)	Concept: what are the operating and maintenance requirements of existing technologies. Construct: specific details regarding the operating and maintenance requirements of existing technologies.	Focus groups: questions concerning the extent to which each firm has been successful in introducing innovative mechatronics technologies and the elicitation of their specific operating and maintenance requirements (Q11).
9. Are Japanese contractors providing training and education for construction operatives?	<i>Hypothesis Nine</i> Contractors are already educating and training the next generation of construction operatives to facilitate the future deployment of automation and robotics.	A purposive sample of Japanese general construction contractors (Big-six by annual sales)	Concept: what education and training is provided for project engineers, machine operators and site operatives Construct: specific details regarding the training of staff and operatives involved in the application of existing technologies.	Focus groups: questions concerning the education and training of construction project staff and operating. Open question regarding the education of site/project engineers, machine operators and maintenance staff (Q12).

Table 3.5 (cont.): Focus group research questions, hypotheses, sample frames, concepts, constructs and operational definitions

Research Question	Hypothesis	Sample	Concept/Construct	Operational Definition
10. Do Japanese contractors aim to export their automated construction services abroad and, subsequently, provide technical support?	<i>Hypothesis Ten</i> The ability to undertake construction projects using automation and robotics and the hiring and leasing of specialist systems is providing competitive advantages within international construction operations.	A purposive sample of Japanese general contractors (Big-six by annual sales)	Concept: what efforts have been made to export existing technologies for overseas operations or for use by foreign contractors. Construct: specific details regarding the deployment of Japanese automation and robotics overseas.	Focus groups: questions concerning export of existing technologies in collaboration with manufacturers and provision of technical support. Specific (closed) question concerning undertaking of such activities (Q13 & Q14).
11. What are the future research directions for Japanese contractors automation and robotics research and development?	<i>Hypothesis Eleven</i> Computer integrated construction and integrated construction automation systems are pertinent to the future strategic objectives of the Big-six Japanese general contractors.	A purposive sample of Japanese general contractors (Big-six by annual sales)	Concept: what are the strategic research objectives of the Big-six general contractors. Construct: specific objectives of ongoing research and the development of CIC and IACS's	Focus groups: question concerning the strategies of the interviewed construction contractors. Open question concerning research strategy and the role of computer integrated construction concepts. (Q15 & Q16).

Table 3.5 (cont.): Focus group research questions, hypotheses, sample frames, concepts, constructs and operational definitions

Focus group	RQ1 (H1)	RQ2 (H2)	RQ3 (H3)	RQ4 (H4)
MoC, PWRI	N/A	N/A	Intangible – increased operator safety. Tangible - machine efficiency	Evaluation of performance capabilities undertaken within PWRI research laboratory conditions prior to provision of operating licence and application on public works projects
MITI, MEL	N/A	N/A	Intangible – operation within hazardous environments.	Research, development and evaluation of machine performance in laboratory conditions.
Obayashi Corporation	Research scientists (varied scientific fields) & computer systems engineers	1999 R&D budget ¥10.175 Billion, equivalent to 0.74% annual sales. ↓	Intangible – operative safety. Followed by tangible cost benefits.	Prototype technologies are tested in-house within the technical research institute.
Tokyu Construction Co. Ltd	Mechanical, electrical, civil structural research engineers	R&D expenditure information not disclosed	Intangible – increased operative safety of primary importance followed by cost reductions.	Prototype technologies are tested in-house and operating difficulties resolved within the research laboratories.
Taisei Corporation	M&E combined with mechatronics research engineers	1999 R&D budget ¥8.9 Billion, equivalent to 0.5% annual sales. ↓	Intangible – valuable operational learning experience	Research and development undertaken at the Yokohama research facility.
Takanaka Corporation	Mechanical, electrical, civil structural research engineers	R&D expenditure information not disclosed	Tangible – lower costs to clients.	Systems are developed in conjunction with machine manufacturers, i.e. Kawasaki, Honda, Komatsu and Mitsubishi. Takanaka suggest suitable machine concepts and assist in the testing and evaluation.

Table 3.6: Focus group response summary analysis grid

Source: author's focus group discussions

Notes: N/A Not applicable to organisation, e.g. public funded research organisation
↓ Downward trend on previous year, e.g. research staff and R&D expenditure

Focus group	RQ1 (H1)	RQ2 (H2)	RQ3 (H3)	RQ4 (H4)
Shimizu Corporation	Mechanical, electrical, civil structural research engineers	1999 R&D budget ¥9.245 Billion, equivalent to 0.58% annual sales. ↓	Intangible – systems developed to enhance company image and technological competitiveness.	Shimizu are primarily a design and management contractor. Machine R&D and manufacturing undertaken by experienced manufacturers.
Maeda Corporation	Research scientists (varied scientific fields) & computer systems engineers	1999 R&D budget ¥2.295 Billion, equivalent to 0.49% annual sales. ↓	Intangible – reduction of human exposure to hazardous working environments, marketing tool, emphasise technological prowess.	Systems designed in collaboration with machine manufacturers. Testing and evaluation conducted within Maeda research facilities.
Kajima Corporation & Takahashi Construction Systems Inc.	Mechanical, electrical, civil structural research engineers	1999 R&D budget ¥16.677 Billion, equivalent to 1.0% annual sales. ↓	Tangible – production efficiency. Intangible – improved quality.	Technology tested and evaluated by manufacturers within laboratories and, finally, construction projects.
Kumagai-Gumi Co. Ltd.	Mechanical, electrical, civil structural research engineers	1999 R&D budget ¥2.883 Billion, equivalent to 0.29% annual sales. ↓	Tangible – labour reductions, increased work efficiency/quality/accuracy. Intangible – increased site safety through improved working environment.	Automated machinery designed, manufactured, tested and evaluated by Construction Machinery Division.

Table 3.6 (cont.): Focus group response summary analysis grid

Source: author's focus group discussions

Focus group	RQ5 (H5)	RQ6 (H6)	RQ7 (H7)	RQ8 (H8)
MoC, PWRI	The development of tele-operated construction plant is providing more efficient earth moving operations and increased operative safety.	Development of project based network for sharing information regarding machine status, productivity data, survey data for record drawings, machine maintenance and quality control.	MoC using tele-operated plant for work within the vicinity of active volcanoes.	The conversion of plant for tele-operation is time consuming and prohibitively expensive.
MITI, MEL	Potential advantages of tele-operated humanoid construction operatives yet to be proven.	N/A	N/A	Humanoid platform requires operators and maintenance engineers with knowledge not previously required with traditional construction plant.
Obayashi Corporation	ABCS and Big-C systems are providing increased productivity, increased operational safety and increased quality. However, systems became cost effective further to three full-scale trials.	Integration of design and construction site processes. Information regarding process engineering shared between designers, engineers and constructors. <i>WebEDI</i> and <i>O-SICS</i> systems.	Selection of single task systems currently deployed on frequent basis (e.g. concrete surface preparation). ABCS and Big-C systems have been successfully deployed on several construction projects.	Technical support provided by in-house research engineers from TRI. Specialist sub-contracted operatives with knowledge of automated system employed.

Table 3.7: Focus group response summary analysis grid

Source: author's focus group discussions

Focus group	RQ5 (H5)	RQ6 (H6)	RQ7 (H7)	RQ8 (H8)
Tokyo Construction Co. Ltd	Prototype systems for material manipulation and tele-operated excavation have been successfully deployed on several construction projects and have provided improved ergonomics, operational safety and productivity.	Material manipulators and tele-operated excavation system do not require complex adjustments to project conditions prior to implementation. They operate under similar circumstances to traditional plant and machinery.	Material manipulators for interior finishing work and tele-operated excavation system have been successfully utilised on several projects.	Existing systems require no greater skill than traditional plant and machinery.
Taisei Corporation	Application of the T-Up system is only cost effective when used on structures >30 storeys. The automated column welding system is not any more economical than traditional welding techniques.	High-rise structures are designed with the use of the T-Up in mind. Construction project managers require broad understanding of the system. The system provides managers with greater control over operatives and the construction process	The T-Up system has been used in the construction of the Mitsubishi HQ in Yokohama. System will only be economical further to recovery of Japanese economy and increase in labour and material costs.	Maintenance requirements are similar to manufacturing manipulators.
Takanaka Corporation	Single task systems and Roof-Push Up system are proving uneconomical. A combination of higher labour costs and demographic changes may provide improved economic feasibility.	There are no radical changes in managerial and organisation structures in order to accommodate automated construction technology.	Concrete distribution, floor screeding and surface finishing robots have been successfully incorporated into operational construction projects	Machine operators require only basic training and maintenance requirements are similar to traditional plant and machinery.

Table 3.7 (cont.): Focus group response summary analysis grid

Source: author's focus group discussions

Focus group	RQ5 (H5)	RQ6 (H6)	RQ7 (H7)	RQ8 (H8)
Shimizu Corporation	Despite extensive utilisation, certain systems are not providing sufficient returns to recover their initial capital investment.	The SMART system includes a site information management system, where project managers are provided with real-time monitoring of site production. Site staff are organised into teams of multi task and specific task operatives.	Single task systems are no longer believed to be economically viable. The SMART and New SMART systems have been successfully deployed on high-rise construction projects	Maintenance requirement for the SMART and NewSMART systems are similar to existing automated manufacturing plant. However, the scale and size of the systems requires more expensive maintenance.
Maeda Corporation	Single task systems (i.e. welding and material AGV's/manipulators proven to be economically acceptable.	MCCS system provides integrated control and management system, i.e. production control, material conveyance, assembly and laser measurement.	Automatic material conveyance systems have been utilised out with the MCCS system. However, greater application of MCCS system impeded by a lack of appropriate structures.	Welding equipment requires greater transfer and preparation time compared to traditional welding. Maintenance requirements are similar to manufacturing robots.
Kajima Corporation & Takahashi Construction Systems Inc.	Automated construction plant and machinery seldom utilised on construction projects. Tele-operated systems are providing increased productivity and quality. However, reductions in site labour requirements are not common.	No managerial or organisational changes were required to introduce the Robocon concrete finishing system. If innovative technology is used, work is generally undertaken by specialist sub-contractor.	Project manager commented that automated technology is seldom used on construction projects.	Robocon system requires inexpensive maintenance. The power unit (Honda petrol engine) requires only traditional maintenance. Control systems would be repaired by machine manufacturer (Tokimec)

Table 3.7 (cont.): Focus group response summary analysis grid

Source: author's focus group discussions

Focus group	RQ5 (H5)	RQ6 (H6)	RQ7 (H7)	RQ8 (H8)
Kumagai-Gumi Co. Ltd.	The use of automated technologies generally increases construction costs. Exceptions include: labour costs reduced as a result of deployment or total construction schedule reduced resulting in cost saving for overall project	Organisational and managerial structures remain similar to situation where traditional plant and machinery is utilised. However, managers must be trained in understanding labour and machine management control systems.	Automated technology only used if: (1) labour costs are reduced as a consequence of deployment or (2) high performance of the machine greatly reduces construction schedule.	Maintenance requirements depend upon the complexity of the automated system. However, maintenance and repair requirements will generally be similar to manufacturing robots.

Table 3.7 (cont.): Focus group response summary analysis grid

Source: author's focus group discussions

Focus group	RQ9 (H9)	RQ10 (H10)	RQ11 (H11)
MoC, PWRI MITI, MEL	N/A N/A	N/A N/A	N/A N/A
Obayashi Corporation	Sub-contractors provide skilled operators and technicians, which are trained by Obayashi and used on every project.	Big-C system has been shipped to Singapore and hired to a construction contractor. Obayashi provide technical support.	Integration of information technology and automated construction systems to re-engineer design and construction procedure.
Tokyu Construction Co. Ltd	Operatives are trained in-house.	Branches in foreign countries may be used as communication route for the deployment of technology. Research engineers would support machine deployment out with Japan.	With development in subterranean construction, the development of remotely operated excavation technology is a valuable and currently feasible research strategy.
Taisei Corporation	Project staff and operatives are trained in-house.	Company not concerned with manufacturing and exporting technology. System manufacturers may consider further to sufficient demand.	Engineers commented that the T-Up will yield benefits further to greater utilisation and improved status of the labour and material markets.
Takanaka Corporation	Project manager, construction engineers and operatives are trained by machine manufactures.	The automated column welding system had been exported to a French construction contractor.	Construction mechatronics research, development and implementation postponed until economic climate is more conducive to the development of such sophisticated and expensive technology.

Table 3.8: Focus group response summary analysis grid

Source: author's focus group discussions

Focus group	RQ9 (H9)	RQ10 (H10)	RQ11 (H11)
Shimizu Corporation	System operators are trained by machine manufactures and in-house research engineering staff.	Automated technology is for Shimizu contracts only. The technology is used to provide competitive gains and the lease/hire of the technology is not acceptable	Networking and communication technologies will assist the development of modern construction management systems. In the short-term, tele-operated and remote control machines will prove valuable. However, automation and robotics will be a valuable source for future operations.
Maeda Corporation	Operative training is undertaken as part of the research and development programme. Maintenance undertaken by machine manufacturers.	Owing to the high capital cost of the equipment, in order to secure high rates of utilisation a rental/hire system will be implemented. International rental/hiring may take place in future.	Further development and evaluation of MCCS system and support networks. The development of man-machine systems to enable reduction in on-site labour requirements.
Kajima Corporation & Takahashi Construction Systems Inc.	Sub-contractors are generally employed to use specialist machines. Therefore, they provide training for their operators in collaboration with machine manufacturers.	Tokimec Construction Systems Inc. (Robocon manufacturer) currently export technology overseas.	Greater research and development of automated control systems for existing plant and machinery. Increase man-machine systems using tele-operation.
Kumagai-Gumi Co. Ltd.	Engineers and operators are trained by the Construction Machinery Division.	Technology developed to enhance competitiveness of firm. No intention to market and export technology overseas. Exportation is not an objective of the Construction Machinery Division.	Development of automated technology for large-scale civil engineering projects aiming to reduce costs through labour reductions and productivity improvements.

Table 3.8 (cont.): Focus group response summary analysis grid

Source: author's focus group discussions

	1995	1996	1997	1998	1999
Kajima Corporation					
Annual sales*	2,091	1,764	2,101	1,939	1,659
R&D investment*	22.711	20.477	20.285	19.315	16.677
% of annual sales	1.09	1.16	0.97	1.00	1.01
Obayashi Corporation					
Annual sales	1,422	1,244	1,541	1,487	1,380
R&D investment	13.6	12.699	11.971	11.877	10.175
% of annual sales	0.96	1.02	0.78	0.80	0.74
Shimizu Corporation					
Annual sales	2,082	1,826	1,718	1,757	1,599
R&D investment	13.498	12.697	11.579	11.388	9.245
% of annual sales	0.65	0.70	0.67	0.65	0.58
Taisei Corporation					
Annual sales	1,998	1,907	1,982	1,831	1,773
R&D investment	12.6	12.144	11.9	10.1	8.9
% of annual sales	0.74	0.64	0.55	0.60	0.50
Kumagai Gumi					
Annual sales	927	1,090	1,059	1,134	998
R&D investment	3.5	3.7	3.89	3.341	2.883
% of annual sales	0.38	0.34	0.37	0.29	0.29
Maeda Corporation					
Annual sales	530	527	494	505	471
R&D investment	3.92	3.281	3.075	2.664	2.295
% of annual sales	0.74	0.62	0.62	0.53	0.49

Table 3.9: Participating organisations general R&D expenditure, 1995 to 1999

* Unit = ¥ Billion

JFY	Total R&D Investment	Construction Automation R&D Investment	Construction Automation Investment as % of Total
1994	15.6	0.34	2.2
1995	12.6	0.23	1.8
1996	12.1	0.12	1.0
1997	11.9	0.15	1.3
1998	10.1	0.18	1.8
1999	8.9	0.14	1.6
2000	8.38	0.06	0.8

Table 3.10: Taisei Corporation annual R&D investment (¥ Billion)

Source: Taisei Corporation, Taisei Research Institute

Hypothesis		Outcome
<u>Hypothesis One</u>	Japanese contractors continue to employ a high percentage of mechanical and electrical engineers, which conduct in-house automation and robotics research and development.	Rejected
<u>Hypothesis Two</u>	Japanese contractors continue to contribute substantial investment towards the research and development of construction automation and robotics.	Rejected
<u>Hypothesis Three</u>	Japanese contractors place greater emphasis upon the intangible benefits of construction automation and are more concerned with strategic, rather than, short term advantages and benefits.	Accepted
<u>Hypothesis Four</u>	Prototype automated technology is extensively tested within laboratory conditions prior to trial on-site implementation projects.	Accepted
<u>Hypothesis Five</u>	Automation and robotics is providing Japanese contractors with the originally perceived efficiencies relating to construction productivity, labour costs and increased operational safety.	Rejected
<u>Hypothesis Six</u>	Japanese construction projects are being re-engineered to accommodate automation and robotics.	Accepted
<u>Hypothesis Seven</u>	Construction automation and robotics is extensively utilised throughout domestic Japanese construction projects.	Rejected
<u>Hypothesis Eight</u>	Existing construction automation and robotics technologies, currently employed on Japanese projects, require highly skilled operators and maintenance personnel.	Rejected
<u>Hypothesis Nine</u>	Contractors are educating and training the next generation of construction operatives to facilitate the future deployment of automation and robotics.	Accepted
<u>Hypothesis Ten</u>	Japanese contractors are aiming to hire and lease specialist construction systems to proliferate automated construction technology deployment within international construction markets.	Inconclusive (manufacturers)
<u>Hypothesis Eleven</u>	Computer integrated construction and integrated construction automation systems are pertinent to the strategic objectives of Japanese contractor's construction automation research and development.	Accepted

Table 3.11: Summary of focus group hypothesis testing

Company	System Name	Super Structure	Project Name & Duration
Obayashi Corporation	ABCS	2B, 28F, 79752 m ² , steel and pre-cast concrete	NEC Head Office, Kanagawa, October 1997 to January 2000
Obayashi Corporation	ABCS	2B, 10F, 10226m ² , steel and pre-cast concrete	Riverside Sumida Bachelor Dormitory, June 1993 to April 1994
Obayashi Corporation	Big-Canopy	30F, 42655m ² , pre-cast concrete	DBS Square office building, Singapore, November 1997 to September 1999 (first application outside Japan).
Obayashi Corporation	Big-Canopy	1B, 37F, 28505m ² , pre-cast concrete	Nada-Hinode Cho condominium, Kobe, April 1997 to June 1999
Obayashi Corporation	Big-Canopy	22F, 12641m ² , pre-cast concrete	NEXAS Kashii Central Tower condominium, Fukuoka, September 1996 to March 1998
Obayashi Corporation	Big-Canopy	26F, 30726m ² , pre-cast concrete	Yachiyodai condominium, Yachiyodai, February 1995 to February 1997
Obayashi Corporation	Big-Canopy	1B, 27F, 25540 m ² , pre-cast concrete	CAMZA Square Towers, condominium, Chiba, Jan 1995 to Feb 1997
Shimizu Corporation	New SMART	1B, 35F, 29076m ² , pre-cast concrete	Makauhari SH-1 project, condominium, November 1998 to March 2001
Shimizu Corporation	New SMART	3B, 34F, 253054 m ² , pre-cast concrete	HDB Center, Singapore, project duration data unavailable (first application outside Japan)
Shimizu Corporation	Simplified SMART System	6F, 4408 m ² , steel and pre-cast concrete	Hotel Mets, Kawasaki, project duration data unavailable
Shimizu Corporation	Simplified SMART System	3B, 16F, 52115 m ² , steel and pre-cast concrete	Denso New Building, project duration data unavailable
Shimizu Corporation	SMART	30F, 74927m ² , steel	Nisseki Building, Yokohama, July 1994 to June 1997
Shimizu Corporation	SMART	20F, 20657m ² , steel	Juroku Bank Building, Nagoya, October 1991 to February 1994
Taisei Corporation	T-Up	2B, 34F, 110918m ² , steel, <i>in-situ</i> , and pre-cast concrete	Mitsubishi Heavy Industries Yokohama Building, April 1992 to March 1994
Takanaka Corporation	Roof Push-up Method	2B, 16F, 11880m ² , steel and pre-cast concrete	Dowa Fire and Marine Insurance Building, November 1993 to February 1995
Takanaka Corporation	Roof Push-up Method	2B, 13F, 7940m ² , steel, <i>in-situ</i> and pre-cast concrete	Yanagibashi Mitsui Building, Nagoya, October 1989 to May 1991.
Kajima Corporation	AMURAD	9F, steel and pre-cast concrete	Kajima Chigusa Company Housing, Nagoya, December 1995 to October 1996.
Maeda Corporation	MCCS	4B, 9F, 10807m ² , steel and pre-cast concrete	Tepco-Building Ltd, Tokyo, April 1995 to March 1998
Maeda Corporation	MCCS	2B, 11F, 6614m ² , steel and pre-cast concrete	Sekai-Bunka-sya Corporation, Tokyo, June 1992 to February 1994
Fujita Corporation	Akatsuki 21	1B, 16F, 13065m ² , steel and pre-cast concrete	Shuyo-dan Building Construction Work head office, March 1994 to June 1996 (including demolition of old structure)

Table 3.12: Summary of integrated automated construction system applications

Source: Furuya *et al* 2000; Miyakawa *et al* 2000; Japan Council for Construction Robot Research 1999; Cousineau & Miura 1998; Tanijiri *et al* 1997; and corporate brochures.

CHAPTER 4

CONSTRUCTION AUTOMATION ECONOMICS

4.1 Introduction

In the risky, volatile and highly conservative construction environment the economic benefits of automation must be clearly visible to management, even when not easily quantifiable, to justify the significant long-range commitment to implementation (Warszawski 1999). The economic costs and benefits of construction automation technology are complex and are unlike those experienced with traditional construction plant and machinery.

Existing literature evaluate the cost effectiveness of construction automation technology by assuming that the tangible benefits must exceed the utilisation costs (Warszawski 1999; Warszawski & Rosenfeld 1994; Rosenfeld *et al* 1992). The success of construction robots depends upon their value to the construction contractors. Specifically Najafi and Fu (1992), state that economic valuation is performed by comparing a costs analysis of non-robotic versus robotic work alternatives. These utilisation costs incorporate R&D expenditure, development costs, operating and ownership costs. However, with machine manufacturers conducting research and development, the growth of the plant-hire industry and the increased use of sub-contracting these costs may be dispersed amongst the involved firms. Furthermore, the intangible economic benefits of such technology may provide valuable opportunities for these firms.

Hiring expensive and technologically complex construction plant may provide greater flexibility to contractors, who may not have the initial resources to purchase such technology and may wish to avoid the associated high maintenance, storage and depreciation costs.

Innovative technology may facilitate an increased capacity of contractors to produce: firms can either produce more at the same price or produce the same output at a lower price (Gruneberg 1997). Therefore, the application of innovative plant may increase the capacity of the industry. However, reductions in construction costs will enable clients (developers) to offer increased bids to landowners in order to purchase sites. Subsequently, the benefits of lower construction costs will be the landowners. The management of technological innovation may be a source of growth and additional profit for UK construction firms through providing improved productivity, reduced costs, access to new markets and improved competitive positioning (Gann & Simmonds 1993).

This chapter outlines the economic considerations when investing in construction automation technology. The chapter attributes the economic costs and benefits to the appropriate organisations involved in the research, development and implementation of automation and robotics for the UK construction industry. As outlined in Chapter 2, the complex costs and benefits of construction automation technology have historically been combined and apportioned to the end user of such technology, i.e. the contractor.

4.2 Overview of the UK construction industry

The construction industry has traditionally been more volatile than in other sectors. Periods of growth in the construction sector are often followed by periods of recession. The

construction industry is sensitive to expectations of future demand and to interest rate changes. Low interest rates increase the return from capital investment and encourage capital spending, especially when they are combined with increased demand and extensive usage of the existing capacity. Table 4.1 presents a summary of the gross value added (GVA) for each UK industrial sector at current basic prices. As a percentage of all industrial sectors, the UK construction industry contributes to approximately 5% of the UK gross domestic product (GDP). There is expectation that the construction industry's value added will decline gradually, squeezed by the exacting demands of clients and the increasing industrialisation of most inputs, as raw materials will be supplanted by component and subsystems to be assembled rather than constructed (Simmonds & Clark 1999).

Gross fixed capital formation (GFCF) is the amount of new factories, roads, plant, equipment and housing produced within the country. Buildings not only contribute to the GDP during their construction, but also contribute to the country's stock of wealth as the stock of buildings in a country accumulate for use in future years. GDP is the value of goods and services produced for final use in consumption, capital expenditure and exports from one year to the next. In any single year the manufacturing and construction industries produce consumer and capital goods. Whilst consumer goods are those bought by households for their own use, capital goods, such as buildings, plant and machinery, add to the productive capacity of the economy. The construction industry produces capital goods, which enable the economy to expand. Table 4.2 indicates that the construction industry plays a significant role in domestic fixed capital formation (e.g. roads, bridges, railways, buildings, water and sewage treatment plants). It is this built infrastructure which enables industrial production to take place and enables goods to be transported from factories to consumers. The construction sector, therefore, play a vital role in the rate of fixed capital

formation and the growth of the national economy. In fiscal year 1992, the UK construction industry contributed to 45.93% of the total gross domestic fixed capital formation (GDFCF) for both public (non-financial) and private sectors. By 2000, this value had decreased to 34.67%.

The sheer scale of the construction industry brands it an important economic entity. According to Table 4.3, in fiscal year 2000 the construction industry provided 1.852 million jobs and approximately 6.35% of total jobs in the United Kingdom. When the construction industry experiences growth, it stimulates demand in other industrial sectors, because such a high proportion of the input to the construction industry is in fact produced by other industries. The construction industry may often be seen as stimulating the economy, because it is a labour intensive industry, and increases in demand for construction create employment, which in turn raises the level of incomes in a region (Gruneberg 1997).

4.3 The nature of construction projects

The construction industry is fragmented with construction projects involving many parties, although none have a dominant role in the success of the project. Segmented organisation of the building process is a major hindrance for innovation (Pries & Janszen 1995). The industry has an inherent transient nature, with regards to the location of projects and the personnel assigned to each specific project.

To a certain extent construction projects have a non-repetitive feature which diminishes the benefits from learning curves (Tucker 1988). Cyclical demand patterns lessen any support for long term investment and the commercial climate tends to be low profitability margins

and protectionism (CRISP 2000a). Furthermore, fluctuations in demand are a disincentive for contractors to undertake substantial investment in new technologies (Dodgson & Rothwell 1994).

The construction industry has specific characteristics, which separate it from other industries. According to Harvey and Ashworth (1997), these are:

- the physical nature of the product;
- the product is normally manufactured on the clients' premises, i.e. the construction site;
- projects are often one-off designs and lack an prototype model being available;
- the arrangement of the industry, where design has normally been separate from construction;
- organisation of the construction process; and
- methods used for price determination.

Paulson (1985) and Warszawski and Sangrey (1985) claim that the lack of interest in automating construction work is mainly due to the particular features of construction activities. These were highlighted as the unique nature of every project, production moving from one location to another, frequently reconfigured field operations, divided authority over the process (between owner, designer and contractor), the rugged construction environment, exposure to environmental conditions and the volatile nature of construction markets. Furthermore, the triability of the construction industry is low, i.e. clients are compelled to stick to proven techniques due to the long life-span of buildings and the expense associated with remediation work (Pries & Jensen 1995).

4.3.1 Factors of production

There are four elements that are necessary for production, these are land, labour, capital and the entrepreneurial function. Figure 4.1 outlines the factors of production, which are essential in the operations of the UK construction industry. Economic capital is said to be wealth, which is then used in the creation of further wealth. In the construction industry, this is defined as the plant, machinery and raw materials, which are used in the construction process.

Construction contractors generally avoid working practices, which involve substantial investment in fixed capital. Therefore, capital in the form of plant and machinery is obtained from the plant-hire industry as and when required. As contractors, generally, do not own plant and machinery, then it may prove increasingly difficult to introduce new automated production processes. Subsequently, production process improvements within the construction industry have been less significant in comparison to the manufacturing industry, where plant and machinery is owned. However, the use of specialist subcontractors is wide spread and, owing to the repetitive nature of their operations, may allow specialist automated production technology to be highly utilised without main contractors incurring the operating and ownership costs of such technologies.

4.4 Economic effect of innovation in construction

Innovation may be defined as the practical application of new inventions. Technological innovation involves introducing a technical idea into an area of industrial activity where the idea has not previously been used in the expectation of some commercial advantage. Winch (1998) defines innovation as the management of new ideas into good currency. Intense competitive rivalry and the project-based nature of construction projects provide

strong incentives for innovation (Tatum 1987). From a contractor's point of view, successful innovation concerns choosing technologies which embody the potential of a sequence of developments that meet market possibilities as the product or process diffuses into the commercial environment (Cusack 1992). Innovation creates possibilities for competitive advantages (Pries & Janszen 1995). The economic significance of an innovation depends upon the continued development following initial introduction to the market place.

Schumpeterian economics distinguishes between invention (generating new ideas) and innovation (applying the new ideas) (Winch 1998). Schumpeterian economics views profit as the reward for bringing new products or processes to the market (Beardshaw 1996). Schumpeter (1939) attributed fluctuations in economic growth around an explicit recognition of the contribution of technical innovation. Success or delay of an innovation is dependent upon the continuous coupling of technological opportunity and market need (Cusack 1992).

The problem with the construction sector is not that there has been no innovation, but rather the rate of innovation, which lags behind other industrial sectors (Seaden 1997). Table 4.4 shows a comparison of UK manufacturing and construction industry labour productivity. From 1995 to 2000, the construction industry employment increased from 1,766,000 to 1,852,000 and total output at basic prices increased from £86,139 million to £115,788 million. With the employment figures rising in conjunction with the total output, employee productivity increased from £48,776.33 to £62,520 per employee. However, despite UK manufacturing industry employment decreasing from 4,470,000 to 4,138,000 and the total output at basic prices increased from £382,455 million to £403,299 million, there was an increase in employee productivity within the sector. Productivity ratio increased from

£85,560.40 to £97,462.30 per employee. Therefore, having decreased the labour force, manufacturing productivity must have risen due to a substitution of labour for capital. The overall greater labour productivity experienced in the UK manufacturing industry may be due to the improvements generated by automation and robotics.

Langford and Male (2001) identify four distinct types of innovation that occur within the construction industry:

1. *Technological innovation* – the use of new knowledge or techniques to provide a lower cost or higher quality product.
2. *Organisational innovation* – changing the relationship between behaviours, attitudes and values of people in the firm, i.e. new types of business organisation, new forms of contract and procurement (partnering, prime contracting and PFI).
3. *Product innovation* – advances in technology, which result in superior products or services.
4. *Process innovation* – concerns increasing efficiencies, but may not incorporate significant technological advances.

The capacity of the construction industry may be increased by increasing the quantity of machinery used per worker, and by education and training of the workforce. Increasing the output of the construction industry also depends upon innovation and technical change (Gruneberg 1997). The most important capacity issue facing the construction sector is the supply of skilled labour, including professionals, experienced management and skilled site trades (DTI 2001). Through the use of innovative construction plant and machinery, firms can either produce more at the same price or produce more at a lower price. The capacity

of the firm to learn is, arguably, the most important determinant of its ability to innovate on projects (Winch 1998).

4.5 Construction automation research and development

Regarding the use of construction automation technology, it is important to demonstrate the capabilities of such technologies and validate their operational effectiveness. Within the UK, construction automation R&D expenditure is relatively low in comparison to the activities of the Japanese general contractors. The following section examines the public and private R&D investment practices of the UK and Japanese construction industries.

4.5.1 UK construction industry R&D

R&D in construction is relatively low in comparison with other major UK industries and, in particular, in comparison with major overseas competitors. Small firms with low asset base and low profit margins are unlikely to use other than traditional 'tried and tested' techniques than invest in R&D. Large companies may be able to afford to hire specialists and conduct detailed research, which would not be financially possible for a smaller firm. Therefore, this may result in the larger firms remaining market leaders, as they maintain a flow of technological developments, which enable them to remain ahead of their competitors (Shutt 1995). Gann and Simmonds (1993) concluded from industrial consultations that very few contractors or design organisations commission or carry out research as they do not consider it to be relevant to their business. Interviewed managers indicated that they were not willing to divert scarce resources to establish R&D capability. According to Dodgson and Rothwell (1994), UK construction R&D is undertaken by materials and component producers who develop products aimed at improving the performance of buildings and structures. The beneficiaries of this type of R&D investment

are the end-users rather than the construction contractors. In addition, there is little expenditure on developing new processes aimed at reducing costs and improving the speed and quality of construction.

The total business expenditure on research and development (BERD) is very small considering the size of the sector. Table 4.5 summarises the UK business expenditure on research and development (BERD) for the chemicals, fabricated metals, machinery and equipment and construction industries from 1992 to 2000. In 2000, construction BERD was £34 million and provided 0.3% of total R&D expenditure performed by UK businesses. In comparison, the machinery and equipment sector BERD was £703 million and contributed to 6.108% of the total UK BERD.

Public funding for construction industry research and development is distributed among several organisations. Over the past 10 years public funding for construction research has been, in total, between £50 and £70 million annually (Fairclough 2002). Table 4.6 provides details of UK government funding of construction industry research and development. The Building Research Establishment (BRE) was established in 1927 to test materials, test structural components, raise UK construction standards and act as an independent advisor to public policy makers. Since the privatisation of the BRE in 1997, it has received 64% of the former DETR construction research funding, amounting to approximately £80 million (Fairclough 2002). The main recipients, outside the BRE, of DTI/DTLR funding are: Building Services Research and Information Association (BSRIA); Construction Industry Research and Information Association (CIRIA); Timber Research and Development Association (TRADA); HR Wallingford; Steel Construction Institute (SCI). Table 4.7 shows the total funding, by organisation, received by the various independent research organisations from the DTI/DTLR since July 1997.

The UK government construction innovation and research programme aims to secure an efficient market for the industry, with innovative and successful UK firms that meet the needs of clients and society and which are competitive within domestic and international markets. A component of the government programme of construction-related innovation and research is conducted under the theme of 'New Technologies and Techniques', in which £1.7 million was spent in new contracts let in 2001/02 (DTI 2001).

In collaboration with the Economic and Social Research Council, DETR and DTI, the Innovative Manufacturing Initiative (IMI) was established to improve the performance of the UK manufacturing and construction industries and is supported by a tightly focused and managed multidisciplinary industry led programme. The initiative was launched in May 1993.

A main feature of the IMI is to transfer ideas and culture in manufacturing industries into the construction industry, by harnessing IT, materials engineering and sensor technology to construction processes. The objectives of the IMI Construction as a Manufacturing Process programme are:

- reduce financial and operational risk in procurement to increase value for money for clients;
- reduce costs, increase productivity and shorten construction periods;
- deliver products which satisfy full life-cycle performance needs of clients;
- improve the technical capability of the workforce; and
- contribute to sustainable development.

The following section specifically examines construction automation R&D undertaken within the United Kingdom since the early 1980's. Despite the overall lack of industry sponsored R&D, there has been considerable academic research into the development and practical application of prototype technologies. Table 4.8 summarises the major construction automation research and development programmes undertaken in the UK.

4.5.2 The Japanese construction industry: an overview

The Japanese construction market is the second largest in the world, following the United States. Within Japan, the total investment in construction including private investment amounts to between 16% to 18% of the GDP (Aoki 1998). This amounts to more than double that of Europe and the United States. Government and private sector investment within the Japanese construction sector, from 1990 to 2001, are presented in Table 4.9 and Figure 4.2. The total construction investment in Japan fiscal year 2000 was ¥67.13 trillion of which 43.8% was public investment and 56.2% was private investment (Japanese Ministry of Land, Infrastructure and Transport 2002). In 1999, the Japanese construction industry employed approximately 6.8 million people, which amounts to 10% of the total industrial workforce, employed in over 500,000 companies (Porter *et al* 2000).

Current restructuring of Japanese firms has led to the more efficient allocation of resources to improve profitability and can be expected to exert pressure upon firms to withdraw from low profitability areas and concentrate resources upon highly profitable and strategic areas (Hayami 2000). Many of the larger construction companies, which are efficient at their core business, are now paying for their bubble year folly of straying into the speculative real estate markets. In order to obtain development projects, many contractors either bought real estate or they acted as guarantors for their developers-clients who were seeking

substantial loans. However, further to the collapse of the Japanese 'bubble' economy period and falls in real estate prices, these construction companies have faced severe financial difficulties caused by the liabilities of their land holdings exceeding their assets (Lai 2002; Aoki 1998).

4.5.3 Japanese construction R&D

Japanese general contractor's research and development expenditure has soared from the early 1980's. Hasegawa (1988) outlined that the reason for this phenomenon was the heated competition amongst domestic contractors caused by the market slump around 1980. In order to remain competitive, contractors were eager to develop low-cost structures and cost-saving construction techniques. Furthermore, there was a significant rise in the application of electronics and precision machinery in other high-tech industries starting from the same period.

Within the manufacturing sector, special low cost financing was made available and prior to the early penetration of robotics a depreciation allowance was provided to write off a percentage of the value of the systems following their first year of installation (25% between 1978-79 and 10% between 1982-83). These measures encouraged early demand and stimulated future demand for more sophisticated machinery (Porter *et al* 2000).

The Ministry of Construction (MoC) manages the integration of research and development into construction processes through communication and legislation. The Japanese government, through the MoC, exerts considerable control over the policies and practices of the construction industry (Gann 1995). The MoC determines the eligibility of firms to conduct public works on the basis of them having research and development facilities and

any price competition incorporates the cost of the associated R&D programs. It may take up to 10 years for the MoC to certify a new technology for use on construction sites after its initial development. However, the rigour of the approval and testing process eliminates the risk of litigation that potentially could arise from the implementation of inadequately tested technologies (Fraser & Fraser 2001).

Private construction companies predominantly fund construction industry research and development. The objective of their research facilities is to verify and improve engineering designs and construction procedures using full-scale experimentation. These performance tests assure that designs and new technologies are adequate and perform successfully under construction site conditions. In order to ensure site safety and eliminate the exposure of the Japanese public to unnecessary risk, Japanese contractors concentrate their R&D efforts primarily in basic experiments, trial works and pilot works. Full-scale testing of automated construction technology has been used primarily to demonstrate the feasibility of the technology rather than its economic benefits (Gann 1995). Research and development expenditure is used to enhance a contractors technological capability and provide competitive advantages over adversaries. Typically, the largest Japanese construction contractors routinely invest between 0.5% and 1% of their annual sales into research and development (Levy 1993; Cousineau & Miura 1998). Figure 4.3 presents research and development expenditure for the six largest contractors (by annual sales) from 1976 to 1999. Despite a decrease in Japanese construction investment, construction related R&D investment peaked between 1991 and 1993. In 1991, the Shimizu Corporation R&D investment reached ¥18.59 billion (£102.143 million). Followed by the Kajima Corporation R&D investment reaching ¥25 billion (£137.36 million), the Obayahi Corporation reaching ¥18.4 billion (£101.09 million) and the Taisei Corporation reaching ¥17.1 billion (£93.95 million) in 1993. Table 4.10 shows the research and development

expenditure of the Big-six general contractors and their R&D expenditure as a percentage of annual sales. In conjunction with declining annual sales and net profits, research and development expenditure has decreased significantly over the last ten years. For example, the Taisei Corporation has reduced its R&D investment from 0.73% of annual sales in 1995 to 0.5% of annual sales in 1999. Figure 4.4 represents the total R&D and construction automation investment for the Taisei Corporation between 1994 and 2000. Construction automation research and development expenditure has been reduced from 2.18% of total R&D investment to 0.71% of total R&D investment.

It is clearly evident that despite the economic climate within Japan and the recession within the construction sector, the Big-six general contractors continue to contribute substantial funding to their research and development facilities. However, there has been a significant reduction in the value of privately funded construction research and development. More specifically, the value of construction automation investment has been significantly reduced in order for the largest general contractors to remain competitive.

4.6 Drivers and barriers for construction automation innovation

There are significant economic drivers and barriers associated with the implementation of construction automation technology. This section highlights a selection of the relevant drivers and barriers highlighted within the existing literature.

In a survey of European academics, Poppy (1994) summarised the major driving forces for automation and robotics in construction as:

- an extensive lack of skilled workers and an increasing average age of staff;

- increased requirement on the quality of work execution;
- a need for work in dangerous and inaccessible areas;
- an increase in performance and a reduction of costs for improved economy; and
- the competition within international construction machinery markets.

The CRISP commission (2000b) characterised the barriers associated with technological change. Those appropriate to the use of construction automation and robotics were:

- *Financial restrictions* – There is a short-term cost associated with the change; payback periods need to be considered in looking at the overall benefit. This applies equally to IT changes and those in production or construction methods.
- *Cultural barriers* – A reluctance to embrace change. People broadly fall into three categories:
 1. *Blockers* – obstructive and unwilling to accept new practices
 2. *Accepters* – prepared to try but fairly neutral reaction
 3. *Enthusiasts* – willing to accept new practices and proactive in their implementation
- *Lack of time* – Time is required to review the implications of the technological change, to describe how to adopt new practices and then put this into practice
- *Risk allocation* – There may be a reluctance to accept the risk associated with innovation based upon previous experiences or managers perception.

Specifically, Poppy (1994) describes the major barriers within Europe as:

- high costs and a shortage of public funding for R&D;

- lack of interest (demand) from the construction industry, unsolved technical problems and special on-site requirements of the technology have lead to problems of acceptance within the industry; and
- lack of appropriate electronic components and systems with adequate durability and life expectancy for operation within a construction environment.

The separation of the productive capacity of the industry from its production processes acts as a brake on innovation (Langford & Male 2001). However, with the advent of sub-contracting, specialist sub-contractors may be more inclined to invest in technologies that may increase their productive capacity and provide increased profits. The use of automated construction systems through the plant-hire industry or specialist sub-contractors provides a more logical means of introducing prohibitively expensive and utilisation rate dependant technologies.

4.6.1 Industry demand

Economic activity within the construction industry triggers a demand for inventive activity. Innovation can arise in a situation of buoyant demand. In this situation, pressure upon the cost and availability of factor inputs encourages the introduction of new technology (Lowe 1996). Alternatively, competitive pressure arises when competition forces prices down and reduces profit margins, and hence, innovation occurs to reduce input costs and increase profits (*ibid*).

Without sufficient demand for construction automation technology from contractors, there will be little incentive for machine manufacturers to undertake R&D and supply such technology. Cobb (1998) concluded that the government should provide the stimulus for

demand, if the general consensus is that construction automation will provide increased safety, quality, productivity and value for money. The viability of investment in construction automation technology will be governed by whether the demand for construction industry services is abundant and stable.

4.6.2 Technology push

The discipline of robotics is advancing rapidly. Recent advances include the Honda humanoid robot (P3), military surveillance robots, earth-quake search and rescue robots, automated vacuum cleaners, robotic master-slave surgical systems and planetary rover exploration robots, (Menzel & D'Aluisio 2000). The development in internal and external sensors, which measure the movement of manipulator joints or various aspects of the work environment (mechanical, optical, tactile, proximity and vision) are facilitating progress in the application of automation to construction processes. However, many of the roles executed by humans within the construction industry may appear to be difficult for machines. Warwick (1997) commented that particular difficulties are encountered when a direct comparison is made with how humans currently execute tasks. This infers that there must be a re-evaluation of the task and a re-design of the work environment to suit automated technologies. Despite technology push, there must be complimentary adaptations of the construction project environment to better suit automation systems.

Changes in the supply of innovations establish the progress of manufacturers in the development of automation and robotics for the construction industry. However, there must be a complimentary construction industry demand for such technologies from contractors. Cusack (1992) outlined that the process of innovation is not just a 'technology

push' phenomenon and that it is closely related to the understanding of the customers (contractors) requirements.

The stimulus for technology push is often a solution to a costly problem or a potentially profitable opportunity being exploited (Chaundler 1982). Obayashi (1992) concludes that robot manufacturers are well aware of the growth potential of the construction automation systems market, but they continue to hesitate in adding the development and production of such systems to their operations.

4.6.3 Industry conservatism

The cyclical and volatile nature of the construction industry may mean that there is a greater tendency to remain with the tried, tested and proven solutions rather than to take a chance on the unproven innovative methods and technologies (Tucker 1988; Naoum 1994). Changes make people anxious and more prone to clutch to familiar ways of doing things. They reach for old solutions to new problems (Statt 1994). The volatile and unpredictable nature of the construction environment causes management to avoid changes and adhere to proven traditional methods and technologies (Warszawski & Sangrey 1985). In a study of the role of individuals in the process of technological innovation within the US construction industry, Nam and Tatum (1997) concluded that conservatism stems from a limited knowledge of the technology in question. Subsequently, the ability to understand the technology usually alleviates these conservative attitudes and even leads to a progressive stance.

However, the construction industry displays remarkable flexibility and resilience for an industry that is often criticised for its resistance to change (Betts & Offori 1992).

Construction contractors often have lower ratios of fixed assets to total assets than other industrial organisations. They have had to adapt and respond to macroeconomic conditions in order to survive and remain competitive.

4.7 Tangible benefits

There are considerable tangible benefits to be gained from the use of automated construction technology. Owing to the developmental stage of the technology, these benefits have yet to be realised to their full potential. The following sub-sections highlight the tangible financial benefits, which have been realised from the application of existing prototype and manufactured automated construction technologies. In order for automated technology to be financially feasible, the tangible benefits to be gained from using the system must outweigh the implementation expense.

4.7.1 Improved construction quality

A significant reasoning behind the application of automation and robotics is the potential quality improvements over traditional construction techniques. Greatly improved quality, defined as conformance to specification, is a tangible benefit to be realised from investment in automated construction plant and machinery. Automated construction technology, through consistently maintained and monitored quality standards, may lead to more uniform and predictable production with obvious reductions in material wastage and re-working.

Paulson (1985) describes the use of automated data acquisition and monitoring technology to observe weld quality, soil compaction, concrete composition and strength, connection bolt torque, structural member alignment and deflection, water and air quality and safety

standards. Most quality control procedures produce after-the-fact rejection, with consequential delays, interruptions and expensive re-work. Immediate feedback would enable remedial action to be taken while construction was underway, and therefore minimise the consequences of defects.

Warszawski (1995) outlines the benefits of higher quality in relation to the use of automated construction technology. These included:

- material savings;
- less repair work;
- reduced maintenance; and
- increased client satisfaction.

However, the above may prove difficult to quantify unless contractors keep records of implementation case studies. The value of higher user satisfaction may be assessed through a willingness of clients to pay more in order to avoid the various inconveniences associated with inferior construction quality (Warszawski 1985).

Kangari and Halpin (1989) outline the need for the finished quality of a construction product to be measured using a numerical model, which considers and compares such characteristics as strength, dimensions, colour, etc. They claim that there is a direct relationship between cost and the quality level attained.

In the extension of King Fahd's Mosque in Saudi Arabia, computer aided manufacturing was utilised in the production of marble and granite stones for the project. Economic analyses of the automated production procedures concluded that they provided equivalent

cost to traditional methods. However, far superior quality and precision was achieved, which reduced material wastage and provided unparalleled artistic detail (Taher *et al* 1994).

With regards to public infrastructure investment, increased construction quality would be beneficial in many ways. For example, if a water treatment facility could be constructed with higher precision and to greater quality specifications, the need for future repair and maintenance work could be reduced in conjunction with increasing the economic life of the facility.

It is evident that owing to greater control over the construction process (on-site or in a prefabrication factory) increased construction quality may be realised. However, the conversion of these benefits into a tangible cost reduction may require scientific comparison with traditional work methods and techniques.

4.7.2 Improved labour productivity

Kangari and Halpin (1989) define productivity as the ratio of output to input, typically given as units produced per man-hours required. In order to determine any possible increases in productivity, they suggested that a direct comparison be made between the traditional procedure and the automated construction technique. They comment that historical data regarding the automated system may not be available and a study may have to be undertaken to determine rates of productivity. However, this may only be appropriate for prototype technologies and contractors may not be willing to deploy technologies, which can not provide a guaranteed level of productivity. It is questionable whether automated technology will not have been tested and studied in order to provide reliable

productivity rates to potential end-users. The tangible benefits associated with productivity gains relative to traditional manual labour may be readily recorded, documented and translated into monetary savings with regards to reduced labour costs (Warszawski & Navon 1998). In consideration of the exposure of construction site to environmental conditions, Warszawski (1999) highlighted that under harsh weather conditions the use of automation and robotics may have a positive influence on the productivity of construction site operations.

Construction automation technology may provide opportunity to increase the productivity of site labour through amplifying the productive capacity of site operatives and through allowing operators to control more than one machine at any one time. However, scientific work-studies are required to provide data to undertake detailed comparative studies.

4.7.3 Reduced labour costs

A key driver for the future adoption and widespread use of construction automation and robotics is high and potentially rising labour costs, which can be expected to accelerate the utilisation of labour saving technology (Kangari & Halpin 1989). However, reductions in labour requirements must be compared with those costs associated with the control, monitoring and the undertaking of work, which the machine is not capable of performing.

4.8 Intangible benefits

Warszawski and Navon (1998) conclude that construction automation might have the best chance of implementation if special economic premiums are placed upon the intangible benefits to be gained from the utilisation of the machinery. However, these benefits provide great difficulty in relation to their monetary value to the user. The following sub-

sections highlight the intangible benefits, which would provide justification of construction automation technology.

4.8.1 Improved operative ergonomics and safety

The risk of a construction operative being injured or incurring serious illness whilst working on a construction site is extremely high due to the nature of construction project operations. Table 4.11 shows construction industry fatalities and major injuries in comparison with all UK industries. It is evident that construction projects are extremely dangerous and hazardous to human operatives. During the period 1999/2000, there were 1290 reported injuries, of which, 392 were wither fatalities or major injuries per 100,000 employees. Construction project accidents, whether or not they involve a human operative, give rise to a cost and a consequence. This cost may be due to a breakage or damage, delays caused by repair or repeat work and having to wait for replacement components. Furthermore, there may be possible effects upon the quality or performance of the finished product. Smith (2000) highlighted that serious construction accidents may cause sites to be closed whilst investigations are undertaken by the HSE and that these accidents represent incalculable costs associated with the subsequent loss of reputation.

A reduction in over exertion injuries caused by repetitive exertion, static exertion, forceful exertion, localised mechanical stresses, posture stresses, low temperatures or vibration may improve construction operative ergonomics (Everett 1994). The elimination of exposure to potential health hazards associated with the various chemical constituents of construction materials (e.g. cement, concrete admixtures, oils, asphalt, sealant materials, adhesives, paints and plasters) may reduce skin, respiratory tract, lung and eye irritations and have an immediate effect upon labour productivity (Warsawski 1999). The use of construction

automation may reduce workers exposure to potentially hazardous operations, and potentially lower detrimental health risks, accidents and fatality's. Through directly removing operatives from hazardous working conditions, tele-operated construction machinery may provide immediate safety benefits for construction site operatives. The use of material manipulators may also eliminate the need for site operatives to perform strenuous and repetitive lifting tasks.

In a survey of the attributes of existing construction automation and robotics technologies, Slaughter (1997) concludes that the vast majority of existing technologies can perform either dangerous and strenuous tasks. These systems may provide a significant reduction in the amount of labour down time, due to ill-health or injury, and increase the overall productivity of the construction project team. Furthermore, automated construction technology may eliminate the need for expensive personal safety equipment and substantially reduce the cost of site safety provisions. However, Warszawski (1999) highlighted the need for special attention to the operational safety requirements of human operators working in close proximity to automated systems.

4.8.2 Learning

Pioneer investments may be valuable through permitting managers to gain experience with a new technology, test the market for new products and keep a close watch on major process advances (Kaplan 1986). If a firm purchases and implements innovative construction plant and machinery, they may be in a suitable position to gain competitive advantage from future innovations. Having operators and maintenance engineers that are

already comfortable with earlier automation devices may allow future developments to be implemented with greater ease¹.

4.8.3 Competitive positioning of the firm

New technology can create new construction demand and create new markets. Conversely, if a contractor falls behind in technology competition, it may mean loss of market share (Everett & Saito 1996). The act of innovating itself can provide strategic benefits and the successful implementation of an innovation can enhance a companies reputation (Slaughter 2000; Hampson & Tatum 1999). Firstly, a specific technology may provide unique capabilities or performance advantages. Secondly, demonstrating a capability to innovate may provide a major competitive advantage (Tatum 1987).

The long term competitive and strategic benefits of innovative construction plant and machinery may reveal stronger incentive to undertake early adoption strategies. Japanese general contractors use construction research and development as a marketing tool for their operations in order to distinguish their technological capabilities from their competitors. Japanese contractors use technological innovation to improve their commercial image and to attract future employees to the industry.

4.9 Technology gatekeepers

The diffusion of technological innovations requires information exchange between the manufacturer and those who are considering implementing their systems. Architects, civil engineers, site agents and plant hire organisations must keep abreast of existing

¹ The strategic value of managerial learning options is analysed in more detail in Chapter 6

developments in order to remain competitive. Technological 'gatekeepers' filter and control the information, which enters an organisation from external sources (e.g. machine manufacturers and material manufacturers). Relevant information for their organisations is either withheld or passed onto appropriate employees. These gatekeepers directly influence the potential for technological innovation within a firm, in the sense that they can either restrict or encourage the flow of information concerning new technologies (Emmitt 2001).

Davidson (2001) examines the acquisition of knowledge for strategic and tactical decision making through a 'technology watch'. Performing the technical gate-keeping role will assist in maintaining the firm's awareness of innovative technical developments and is an important aspect of innovation management (Tatum 1987). The difficulties constraining the provision of a technology watch service for the construction sector were described as the project-by-project way of operating, prescriptive contract documents, small profit margins and the customary competition based upon price alone (Davidson 2001).

Contracting firms require gatekeepers to interface with external R&D activities and to interpret what is going on (Gann 1997). The Laing Technology Group, a consulting engineering and technology division of John Laing Plc, employ a 'technology hunter' whose remit is to scour Laing operating divisions, suppliers and other construction companies within the UK sector for potentially useful new equipment to improve site productivity (Gann & Simmonds 1993).

Among the large Japanese general contractors, it is customary for middle and senior managers from all areas of the company (i.e., design, technology, construction, sales and marketing) to collectively analyse the companies technology needs for the coming years.

These meetings are intended to collect a broad range of technological information from outside the company and to review and evaluate new ideas (Kangari & Miyatake 1997).

The possibility of an independent agent may provide distinct advantages in assisting the UK construction industry in identifying suitable technologies and innovations from overseas that improve construction performance (CRISP 2000c).

Davidson (2001) describes the distribution of information through 'relay stations', which provide information regarding technological innovation to their clients in return for an annual subscription. The International Association of Automation and Robotics (IAARC) provide a service for machine manufacturers and contractors to present information regarding their technological innovations. The service requires membership subscription to IAARC and can be accessed from URL: <http://www.iarc.org.uk>.

4.10 Socio-economic implementation issues

New technology cannot be introduced in a vacuum. For automation and robotics to be successfully applied in the construction industry, the social system it will be part of must be taken into account. The use of automation and robotics will require considerable reorganisation of the construction project environment, involving the displacement of some labour and redefining the tasks of others (Warszawski & Sangrey 1985). When considering the effects of innovative construction technology it must be remembered that the construction industry has frequently had to come to terms with the introduction of innovative plant and machinery.

Frequently new expenditure on technology can be justified only as a capital substitution for labour. New technology is often used as a lever to reduce staffing. The question, however, could be asked can we keep the person, and achieve even higher levels of productivity and production (Cusack 1992). The problems generated by the use of robots centre upon the large-scale displacement of the existing work force. Retraining and replacement are necessary in order to keep unemployment from rising to disruptive levels. Whether the natural economic changes will be rapid enough to absorb the released workers is not yet known. Certainly, such problems generate ethical issues for those directly involved, as well as for the broader society.

Popular stereotypes are based upon fictional literature and non-fictional reports on industrial advances in automated technology. Robots are often depicted as futuristic mechanical men or intelligent machines that inadvertently rob people of their self worth and human spirit (Chao & Kozlowski 1986). The secretive development and subsequent international media demonstration of the Honda Corporation 'P3' and 'Asimo' humanoid robots, are modern day examples of the power of media reports on advanced automated technology. Society's general orientation concerning robots may affect their perception and behaviour towards industrial automaton.

The following sub-sections present an overview of the sociological aspects of implementing automation and robotics within the construction industry. Issues relating to unemployment, re-training, education, resistance reduction, deployment participation are reviewed and discussed. Furthermore, recommendations are developed for their possible incorporation into technology implementation strategies.

4.10.1 Unemployment

In assessing the impact of new technology, it is important to be aware of general underlying trends on supply and demand making an increase in unemployment ever more likely. Innovative technology itself is neutral: it is the way it is applied and used that determines the effects upon the workforce (Robins & Webster 1982). Innovative process technologies generally substitute labour with capital and hence, for a given level of output, may reduce employment. However, the greater efficiency generated from utilising the new process technology may reduce unit costs and, subsequently, increase the overall demand for the product and increase employment. A prime driver for the use of construction automation is to decrease labour requirements and increase the control management have over construction processes, in order to increase competitiveness. A survey of industrial managers within the United States concluded that the desire to reduce the cost of labour was a prime driver for the implementation of automated flexible manufacturing technology (Foulkes & Hirsch 1984). Specifically, a prime driver for construction automation is the reduced reliance upon human site operatives and the need to increase the productivity of the remaining workforce.

The use of automation will involve the displacement of labour and the redefining of remaining tasks (Warszawski & Sangrey 1985). The net effect upon employment must account for jobs, which may be created through the introduction of the new technology. Automated construction technology will generate jobs for those who develop and improve the design of robots, as well as those that repair them (Richardson & Trowell 1994). Prudent construction and plant-hire managers will forecast job requirements prior to introducing automated technology. They will predict the type of jobs, skills and experience that could be required (Foulkes & Hirsch 1984).

It has been debated that the introduction of robotics within the construction industry will relax the demands upon human comprehension and critical judgement and that this may mean a dramatic loss of meaningful employment opportunities (Cusack 1992). The construction industry must take the initiative and re-educate the skilled operatives that are to be replaced by robotic machines in order that new employment openings are provided and the idea of welcoming change rather than fighting it becomes the prevalent attitude of the remaining (Richardson & Trowell 1994).

Intensifying the quantity of machinery used per site operative may increase construction industry productivity. Higher productivity is related to higher output growth, good trading performance and, in consequence, steady or rising employment. New technology, which results in higher productivity, need not lead to long term unemployment; on the other hand, there could be a substantial unemployment problem (Manwring 1981). Construction automation and robotics investment will only reduce unemployment if that investment is sufficient to generate new jobs on a scale greater than the combined effects of the steady displacement labour through technical change the annual growth in the labour force (Cusack 1992). However, it would be complacent to argue that technological change will by itself be sufficient to stimulate the virtuous circle of high output, low unit costs and high employment (Manwring 1981).

Within the US, providing job opportunities is far more valuable politically than investing in technology that may be perceived as a threat to constituents jobs (Bernold 1998). Therefore, there may be little political incentive for the UK government to encourage the use of construction plant and machinery that will ultimately reduce labour requirements and increase unemployment within the construction sector.

With the implementation of information technology through developments in micro-processors in the early 1980's, the TUC aimed to preserve jobs, job content and incomes through collective bargaining. This presupposed that change is negotiated and not imposed (Manwring 1981). Workforce shedding, through compulsory redundancy policies may result in the remaining operatives simply viewing the innovative technology as subsequently causing their work mates and, ultimately, themselves to be unemployed.

Expectation that blue collar work within other sectors may decline with a sufficient proportion of these people being forced into casual work. This situation will be a disincentive to investments in capital equipment and advanced construction techniques (Simmonds & Clark 1999).

At present, the versatility of human operatives far outweighs that of existing automated construction technology. Many of the tasks conducted by human operatives on construction projects would require complex sensory information, artificial intelligence and immense computational power. Therefore, in general, existing automated construction technology requires human programming, control and monitoring. Further to developments in artificial intelligence and sensory technology, humans will continue to provide skills which are currently too technologically perplexing for autonomous systems.

4.10.2 Trade union response to new technology: a historical perspective

If robots are to be utilised in construction, issues relating how to positively encourage their operation must be addressed and lessons must be taken from the successes and dramatic failures of the past (Richardson & Trowell 1994). The advent of more and 'smarter' robots capable of performing sophisticated, interesting tasks may introduce an era of conflict

between employment and management as previously experienced in the manufacturing industry.

The argument that a technology causes unemployment and that any subsequent redundancies are out with the control of the senior management is known as technological determinism. This may be put into effect to cover up the deliberate furthering of management group interests in cutting costs and increasing direct control of the workforce (Statt 1994). Manwring (1981) critically questions the assumption that technological change is socially neutral in its effects. In particular, there can be no presumption that new technology will lead to benefits or that those benefits will be shared.

With each new process that brings change there is the possibility of new jobs as old industries are transformed. The prospect of mass unemployment within the construction industry generated by the intrusion of automated technology may lead to Luddism. During the British industrial revolution, the Luddites, under the direction of Ned Ludd, were enraged by what was perceived as an attack upon their heritage and craftsmanship. In 1811, they went on to smash and destroy machinery on an unprecedented scale. The term 'ludite' is used as a label for those who doubt or oppose the value of mechanisation (Richardson & Trowell 1994).

During the initial adoption stages of introducing flexible automated technology within the UK manufacturing industries, the technology resulted in the loss of many jobs without a reduction in hours or increase in pay and an increase in shift work. The dream of a reduced working week and higher living standards for union members was an unlikely scenario (Manwring 1981).

Union representatives must be involved in designing and planning the adoption of new technology as well as taking part in the decisions regarding its practical application. Labour and management must be aware of the issues and problems that each party considers important. The construction industry must aim to show skilled personnel how machines, seen as potential usurpers, can in fact be companions, who can promote job satisfaction (Richardson & Trowell 1994).

4.10.3 Resistance to change

Technological determinism may be invoked as a cover for the deliberate furthering of management group interests in cutting costs and gaining more control over the workforce. As new technologies often imply the use of fewer workers and the de-skilling of others, a conflict of interest between managers and their workforce is practically guaranteed (Statt 1994). Social acceptance of construction automation and robotics is likely to be influenced by the amount of education the workforce has received prior to implementation (Cusack 1992). Management tools for resistance identification and reduction, have been identified as necessary components for construction automation. Navon *et al* (1993) concluded that the expected human resistance, unless properly dealt with, might hinder the application of automated systems to construction.

In a review of the limited introduction of automation into the construction industry, Navon *et al* (1993) identified general categories of workforce resistance. These were:

- *Fear of unknown changes or uncertainty* – people resisting something that they can not predict or understand.

- *Desire not to lose something of value* – people tend to resist something they perceive as a threat to what they value.
- *Fear of personal inability to handle new requirements* – people who feel that they can not handle challenges of change tend to resist that change.
- *Inadequate understanding for the need for change* – people tend to resist change if they perceive the costs outweigh the benefits.
- *Poor implementation efforts* – inadequate planning of implementation process itself, including inappropriate user involvement and insufficient training, results in resistance by intended users.
- *Labour-management relations* – lack of openness and trust between labour and managers will cause the workers to resist based upon their obstructed concerns.

Initiators may involve the potential resisters in some aspect of the design and implementation of the pioneer venture, they may forestall resistance (Kotter & Schlesinger 1979). The initiators listen to the operatives that are involved in the change and utilise their advice and constructive criticism

In order to minimise the problems associated with change the full and genuine participation of all staff concerned must be initiated as early as possible, i.e. prior to the implementation study. The genuine feeling of shared involvement may create a greater willingness to accept innovative technological change.

Participation may allow the innovation initiators to listen to the people the change involves and utilising their advice, furthermore, participation leads to commitment, not merely compliance (Navon *et al* 1992). Involved employees often come up with valuable suggestions (Foulkes & Hirsch 1984). Construction project management must continually

solicit site operators and operatives for constructive criticism regarding automated processes. However, workforce participation may lead to a poor solution if the process is not carefully managed, but it may also be time consuming (Kotter & Schlesinger 1979).

The extent to which robots were successfully implemented within the manufacturing industries was reflected by the amount of co-operation and communication there was among levels of management, between supervisors and employees, and between management and the engineering staff (Chao & Kozlowski 1986).

Workforce resistance will take a variety of forms; overt and covert, active and passive, conscious and sub-conscious. It ranges from doing less well at the job, to sabotage, to strikes, to trade union organising, to absenteeism. Within the manufacturing sector, positive employee reactions were found when robots assumed hazardous, hot, heavy and monotonous tasks. However, negative reactions were encountered where robots assumed skilled tasks and removed the job satisfaction that employees used to gain from undertaking these skilled tasks, e.g. welding and spray painting (Chao & Kozlowski 1986). During the mechanisation of the British Coal Industry in the 1940's, the heart of all the serious problems concerning productivity and industrial relations was directly related to the disruption of the traditional social organisation of the workplace (Statt 1994).

In order to successfully introduce automated technology to the construction industry, careful consideration of workforce resistance to change must be undertaken. Understanding the existing organisational structure and the effects automated technology may have upon this must be at the fore-front of any implementation studies. Machines excel at physically intensive tasks that require speed, strength, repetitive motions and operation within hostile environments (Everett & Slocum 1994). In a survey of

manufacturing plant employees within the United States of America, positive employee reactions were found where robots assumed hazardous, hot, heavy or monotonous tasks (Chao & Kozlowski 1986). The more onerous the task that a machine undertakes, the more welcomed the technology will be by those who originally conducted such activities.

4.10.4 Re-training and education

Simplification and fragmentation of the manufacturing process, and the subsequent de-skilling or degradation of the individual's working life have often been regarded as the price that had to be paid for enjoying the fruits of the new technology (Statt 1994). The introduction of automation and robotics will diminish the need for physical human effort, but will require the retention of experience-based skills and the re-training of construction operatives for programming, monitoring, maintaining and repairing the automated construction systems. Cusack (1992) highlighted that automation and robotics will naturally displace the human body and its know-how (de-skill), whilst the informational requirements of the technology simultaneously create pressure for a profound re-skilling. Within the manufacturing sectors, the need for operators, technicians, engineers and programmers created opportunities for retraining. Robot technicians consisted of recycled workers previously employed in the same production area that the robots are now operating within (Foulkes & Hirsch 1984). As experienced in the manufacturing industries, the use of computer based equipment often involves additional labour costs for programming, control and updating activities (Slaughter 1997). Greater skill will be required in performance monitoring, identifying malfunctions and any subsequent defect correction. Re-skilling can often provide greater responsibilities and a more challenging and fulfilling goal for people, subsequently making them more effective workers (Cusack 1992).

One of the most common techniques of overcoming resistance to change is to educate the workforce prior to the implementation study. Communication and education may assist in outlining the need for and the logic behind technological innovation (Kotter & Schlesinger 1979). For the human mind to accept change and adaptation, learning is necessary (Richardson & Trowell 1994). Navon (1996) highlighted the need for teaching automation and robotics as part of civil engineering undergraduate courses. Further to undertaking basic mechanical engineering modules, construction students undertake assignments in algorithms for construction management, database management, computer graphics and construction automation and robotics (e.g. manipulators, end-effectors, material supply systems, navigation & control and economic analyses). The later assignment, being devoted entirely to robot applications in the laboratory.

The teaching of construction automation and robotics is an essential component of the training required by the future leaders of the construction industry. Graduates have to be familiar with emerging technologies expected during their professional life, so that they can employ them in the best possible way (Navon 1996). As a consequence of the introduction of automated equipment on-site, Naoum (1994) claims that the amount of directly employed labour would be expected to increase, while the need for casual labour would be reduced, reversing current trends and reducing contractor's flexibility. However, the use of sub-contracting and specialist plant-hire organisations, which hire plant operators and maintain the plant and machinery, may eliminate the need for construction contractors increasing their directly employed labour. The plant-hire organisations will inevitably require their operating and maintenance staff to undergo manufacturers training programmes in order to provide a competent work force capable of maintaining and servicing the automated systems.

The adaptation of human capital to meet the requirements of innovative construction technology is a pertinent issue facing the construction sector. An adequate skills base will be required to implement and support the application of innovative technologies to construction projects. Plant hire organisations will require trained maintenance personnel in conjunction with trained operators, where required. Construction contractors will require site agents, civil engineers site operatives to have an adequate understanding of the operational requirements of the innovative technologies put to use. Furthermore, site labour may require project based training regarding the operational and maintenance requirements of technologies, which are not supplied (hired) with operators, i.e. tele-operated finishing and material handling systems.

Construction project managers, civil engineers, site agents and building managers could be sent to machine manufacturers for training. Workforce education and training will play an important role in the reduction of resistance to innovative technologies and construction processes. A lack of skills will constrain diffusion as effectively as a lack of finance (Deiaco *et al* 1990).

Construction site operatives may become appendages to machines. Proponents of the de-skilling hypothesis argue that firms follow the Tayloristic approach not to increase efficiency through increasing output, but in order to seek control of the workforce through removing knowledge and power from the shop floor (Deiaco *et al* 1990).

4.10.5 Deployment participation

Involved employees often raise valuable suggestions. Therefore, management must continually solicit operatives for new ideas on how to improve their operations. The extent

to which robots are successfully implemented, may be reflected by the level of co-operation and communication among levels of management, between supervisors and operatives, and between management and engineering staff. Communication, education, participation and managerial sensitivity to the concerns of the workforce were important factors for successful implementation within the manufacturing industries (Chao & Kozlowski 1986; Navon *et al* 1993; Richardson & Trowell 1994).

Within a survey of manufacturing plant staff involved in the implementation of a flexible assembly system, a skilled employee who believed that their job would not change viewed the robots as 'just another machine' (Chao & Kozlowski 1986).

Foulkes and Hirsch (1984) commented that it is imperative to establish a positive track record through building employee confidence with an efficiently functioning first installation. The gradual introduction of automated construction technology may mitigate employees' fears, aid project-level acceptance and allow site engineers to discover the operating efficiencies and inadequacies of the innovative technology.

4.11 The role of the plant-hire industry

Construction contractors wishing to minimise their investment in fixed capital, plant and machinery required for construction activities often hire when required rather than purchase outright. Plant hire is seen to be of growing importance as contractors seek to minimise risk and take advantage of the greater flexibility (Lowe 1996). Contractors have sub-contracted a large proportion of their work and avoided working practices that demand substantial investment in plant and machinery (Harvey & Ashworth 1997). Within the UK, a separate plant hire industry has been formed, with plant hire firms purchasing plant and

machinery to, subsequently, hire on a short-term basis to construction contractors. Hiring construction plant and machinery has two main benefits for contractors:

1. increased flexibility, i.e. not burdened with idle plant and machinery following completion of a project; and
2. the avoidance of excess storage, maintenance and depreciation costs when equipment is idle.

Investment in expensive plant and machinery may only be economically viable if it can be used on a continuous basis. Furthermore, specialised automated construction plant and machinery may only provide an acceptable financial return if it is extensively utilised by being moved from one construction contractor to another, where required.

4.12 Construction automation: a segregated economic valuation model

Existing construction automation economic valuation methodologies have assumed that construction contractors bear the costs of the research, development, implementation and operation of innovative construction process technology. Within existing valuation methodologies, it is assumed that the end-user (a contractor) directly incurs the research and development costs, investment/acquisition costs, set-up costs and ownership costs (Warszawski 1985; 1986; 1999; Chao & Skibniewski 1995; Warszawski & Rosenfeld 1998; Ho & Liu 2000). Within Japan, machine manufacturers have collaborated with construction contractors in the research and development of automated construction technology. With the rise of the plant hire sector, the reduction of contractor's fixed capital and the need for high rates of utilisation, it is apparent that automated construction technology will be deployed via specialist plant-hire organisations. These specialist plant-hire organisations will hire these machines, with a qualified operator, on a

hourly/weekly/monthly/annual basis and incur the ownership and operating costs of the machines (depending upon the hire agreement). Finally, the end-users of automated construction technology are the contractors.

Therefore, in the economic appraisal of automated construction systems, it is imperative to segregate the economic costs and benefits and apportion them either to machine manufacturers, plant hirers or contractors. Figure 4.5 presents a summary of the economic benefits and costs associated with the development of construction automation technology and its deployment onto construction projects via a specialist plant hire organisation. In the following sub-sections, the economic considerations for the appraisal of investment and implementation are outlined for each party involved in the research, development, distribution and on-site deployment of construction automation technology.

4.12.1 Machine manufacturers

The first stage of machine development requires collaboration between construction contractors, who provide the remit for the R&D and the machine manufacturers. Further to the assessment of sufficient industry demand and the capabilities of existing technology, a machine may be developed. The following list outlines the economic considerations for machine manufacturers considering construction automation research and development.

- proposal development (collaboration with contractors);
- research, development and trial demonstration of system;
- manufacturing and production;
- marketing and sales;
- servicing and provision of spare components;

- training of operators and maintenance technicians;
- construction industry demand; and
- technology push.

It is evident that machine manufacturers are substantial contributors to the innovation process. The economic cost associated with the research, development and trial demonstration of automation systems rests with the machine manufacturers. Unlike existing valuation models where this cost is attributed to the end-users (i.e. contractors), this cost is the sole responsibility of the machine manufacturer. Servicing and the provision of spare components may be incorporated in owner maintenance contracts or, alternatively, specialist training may be provided for plant-hire maintenance technicians. Operators may be trained by the manufacturer, therefore, ensuring consistent training standards and enhancing the safety of site operations.

The following section describes the economic valuation of automation investment from the view of specialist plant-hire firm. The role of plant-hire organisations will be essential for attaining the high rates of utilisation that may be required for economically viable deployment.

4.12.2 Plant-hire organisations

The significance of the plant-hire industry was outlined in Section 4.11. The role of the UK plant-hire industry, in relation to construction automation investment, has been neglected within existing literature. The following list outlines the economic costs and issues facing UK plant-hire organisations considering construction automation investment:

- rate of machine utilisation;
- ownership costs;
- operating costs;
- fiscal/taxation policies (i.e. taxation allowances etc);
- operator training;
- maintenance technician training;
- purchase cost of new tools and diagnostic equipment;
- additional administration expense; and
- industry demand.

Unlike existing valuation models, it is assumed that the plant-hire firms will incur the ownership and operating costs of such technologies. Their profits will depend upon the annual rates of utilisation and the demand for such technology from sub-contractors and major construction and civil engineering contractors. Operators and maintenance technicians may have to undertake courses provided by the machine manufacturer and there may be a need to purchase specialist tools and diagnostic equipment.

As the ultimate end-user of automated technology, contractors have series of tangible and intangible costs and benefits, which are associated with their involvement in plant and machinery innovation. The following sub-section outlines the economic considerations of contractors.

4.12.3 Contractors

Despite the use of plant-hire organisations, construction contractors may be faced with considerable costs when initially introducing innovative technology, which may be

unfamiliar to employees. The tangible costs and benefits of relevance to a contractor include:

- research and development expenditure (e.g. possible collaboration with machine manufacturer);
- cost of additional labour to work in conjunction with machine;
- hourly machine hire rate;
- workforce training and education (i.e. project managers, site managers/agents, site engineers and construction operatives);
- workforce resistance reduction measures;
- adaptation of project/site environment to suit new construction technique;
- adaptation of structural designs to facilitate automated construction technique;
- reduction of material wastage; and
- reduction in on-site labour requirements.

A significant cost of relevance to a contractor is the initial research and development expenditure, which is incurred only assuming that they are involved in the development of the machine. There may be additional labour requirements to undertake work previously not required and additional training may have to be provided to allow operatives to work within the immediate proximity of automation and robotics technologies. Significant workforce resistance may be experienced and considerable expenditure may be required in the education and participation of existing employees. Finally, there may be considerable expenditure related to the adaptation of the construction environment to facilitate automated technologies. Despite these potentially uncertain and significant costs, there may be benefits associated with labour reductions and improved material handling.

The intangible benefits apportioned to contractors include:

- greater construction efficiency;
- increased labour productivity;
- improved operative safety and work ergonomics;
- greater reliability in construction procedures;
- increased construction quality (i.e. consistently maintained quality standard);
- advantages over competitors; and
- greater client satisfaction.

The economic benefits for contractors may not be immediate and may be more strategic in their relevance. However, the intangible benefits listed above present significant opportunities for increased profit and growth. There may also be significant advantages related to improving the general image of the construction and civil engineering work in order to attract younger generations to the industry. Increased site safety may provide a safer working environment for all construction project operatives and greatly improve the reliability, quality and client satisfaction.

4.13 Conclusions

The current research shows that there are extensive economic implications when considering the future use of automation and robotics within the UK construction sector. From the review presented within this Chapter, the following conclusions can be drawn:

1. For construction automation to be extensively used within the UK construction industry, scientific, technical and financial information must be disseminated

among industry practitioners to provide specific and detailed information on the success of existing technologies.

2. Successful application of existing technologies requires construction managers to overcome the organisational, social and human barriers associated with the application of automation technology to construction operations.
3. Existing economic appraisal methodologies do not attribute the costs and benefits associated with construction automation investment opportunities to the relevant parties.
4. Considering the substantial private investment of the Big-Six Japanese construction contractors and their collaboration with experienced robot manufacturers (e.g. Hitachi, Mitsubishi, etc) it is understandable why they have been successful in researching and developing automated construction technology. Furthermore, there are serious demographic issues, which appear to have encouraged their development.
5. The implementation of automated construction technology will have effects beyond those directly replaced by the machines. Foremen, civil engineers, construction managers and organisational control structures are likely to be affected.
6. In order to provide the high utilisation rates justifying investment in automated construction technology, machines must be hired to construction contractors via specialist plant hire firms. Therefore, contractors will not be required to

maintain and repair the systems. Furthermore, the machines will be utilised by a range of contractors and passed from one site to another to secure high rates of utilisation.

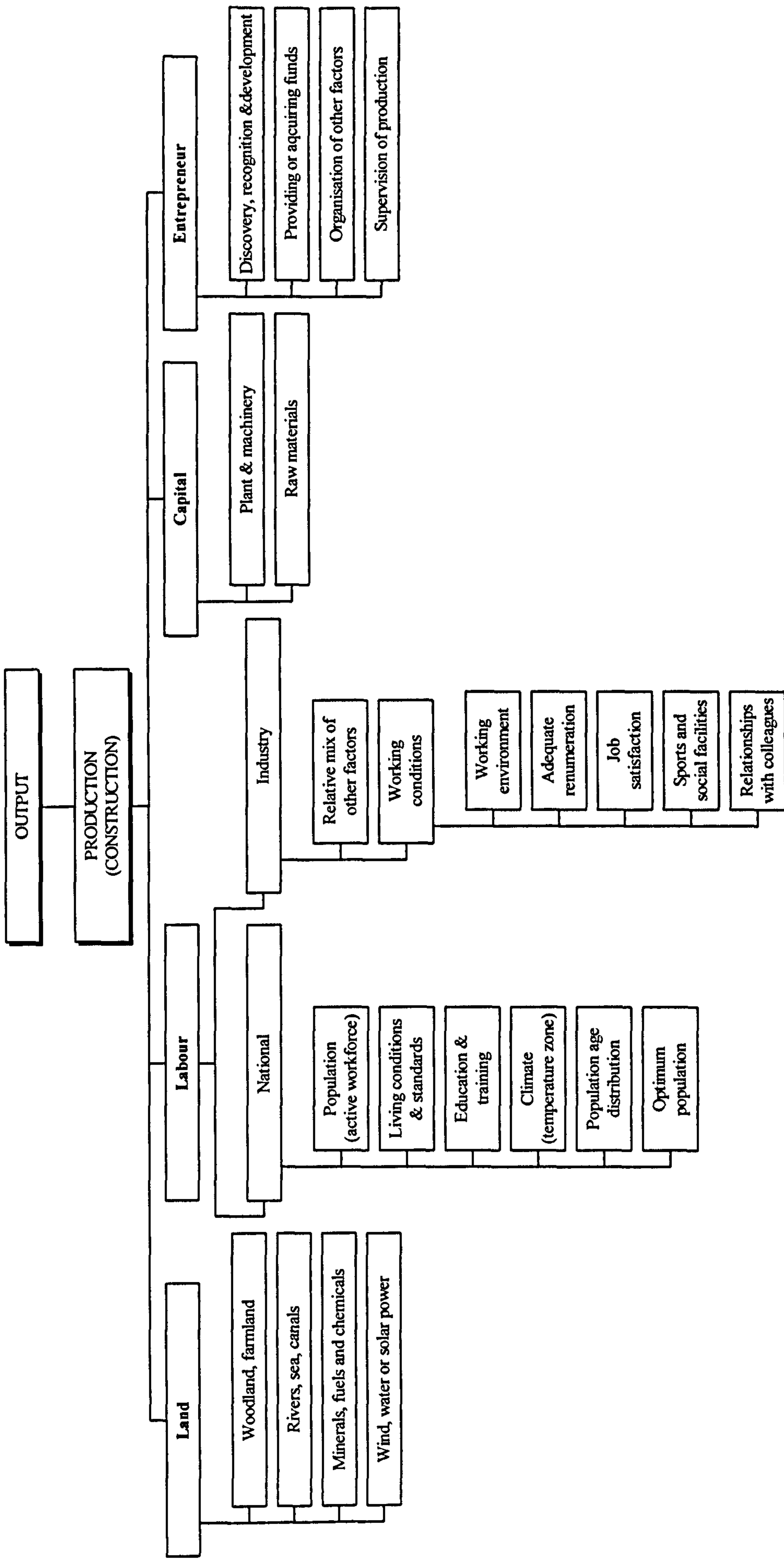


Figure 4.1 Factors of construction industry production
 Source: adapted from Shutt 1995

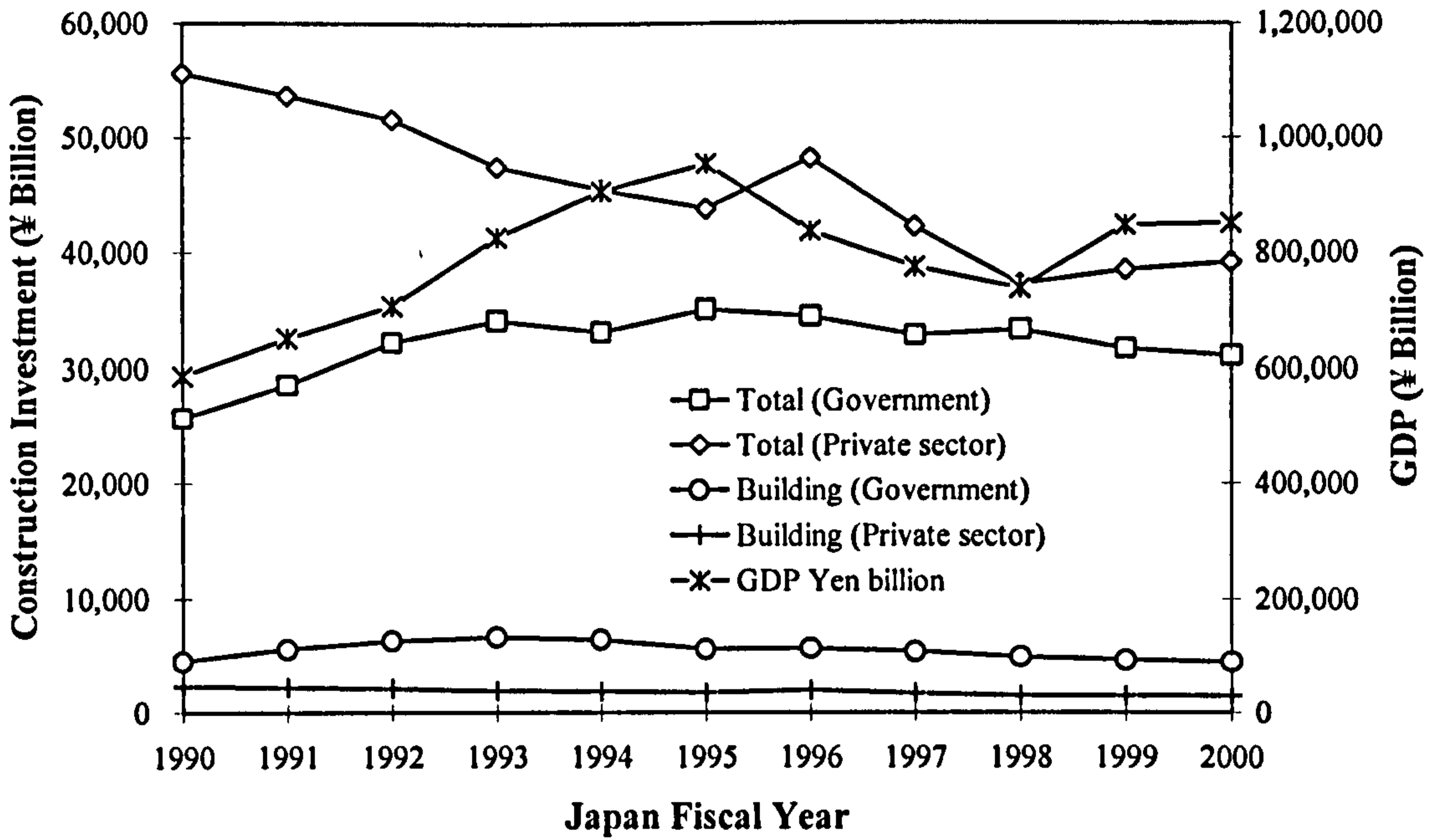


Figure 4.2 Japanese construction investment 1990 to 2000
 Source: Japanese Ministry of Land, Infrastructure & Transport 2000

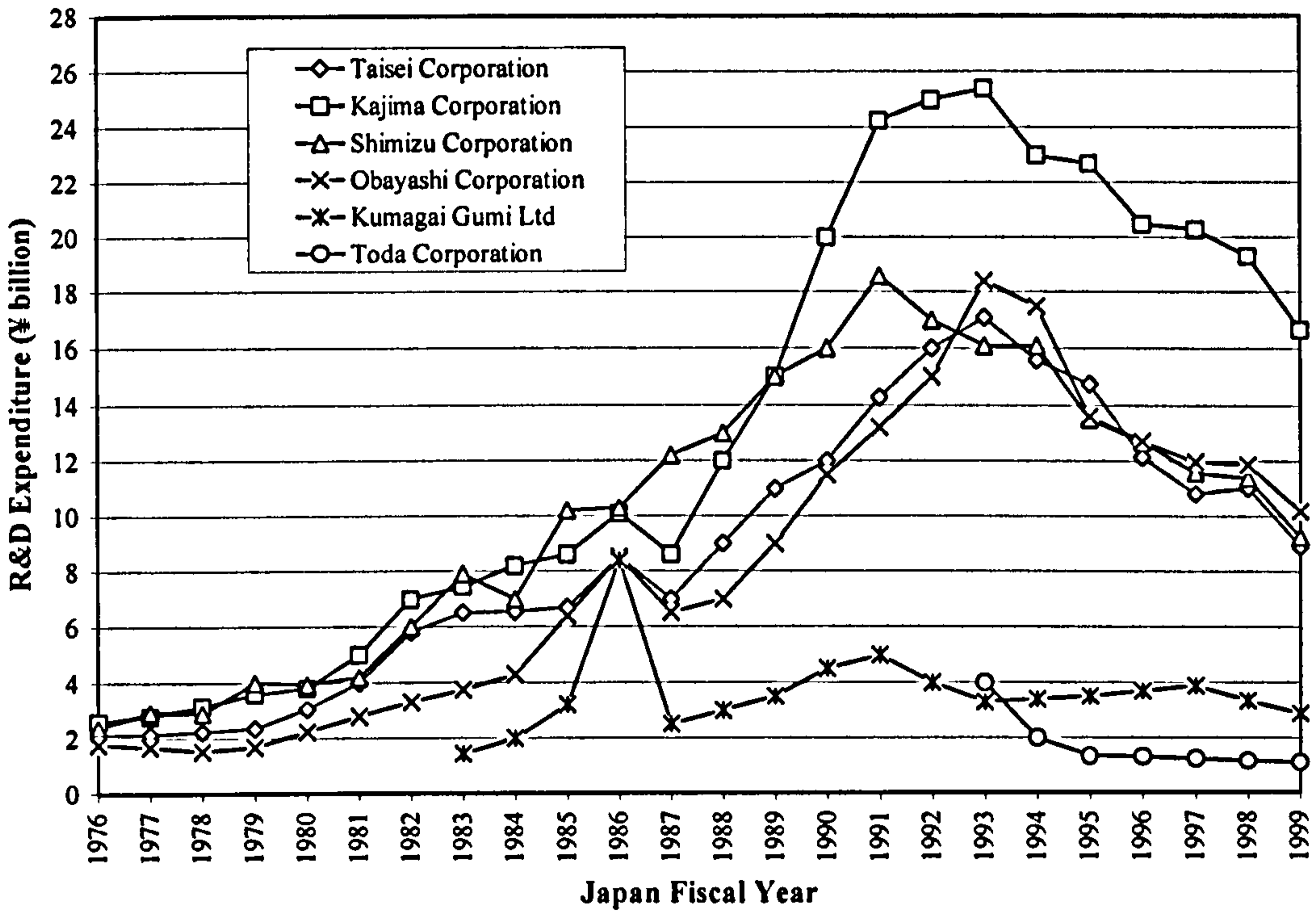


Figure 4.3 Growth of R&D expenditure of Big-Six general contractors
 Source: Annual reports, Hasegawa 1988, Levy 1993 and Gann 1995

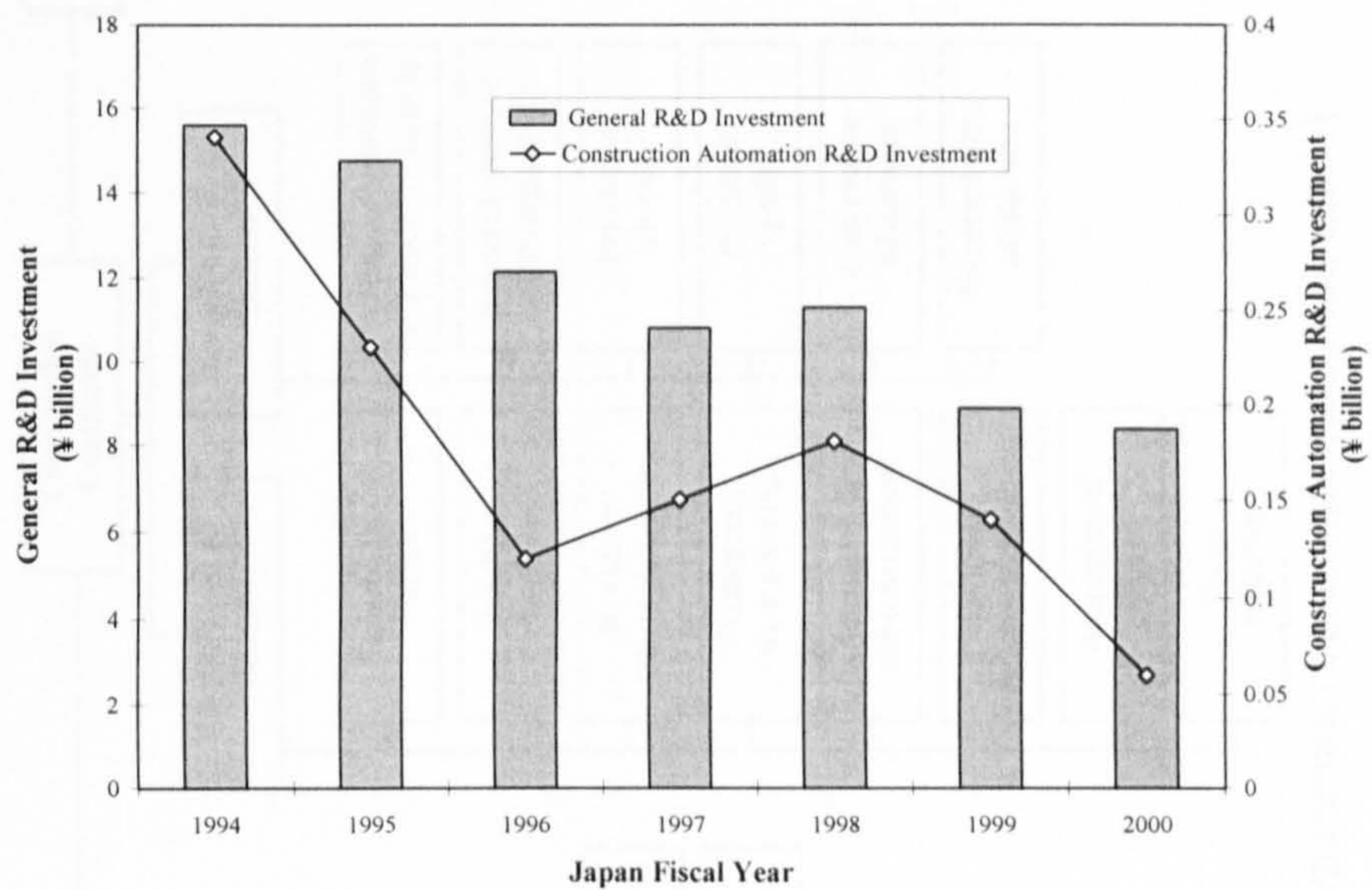


Figure 4.4 Taisei Corporation annual R&D investment & construction mechatronics investment, 1994 to 2000

Source: Taisei Corporation, Taisei Research Institute

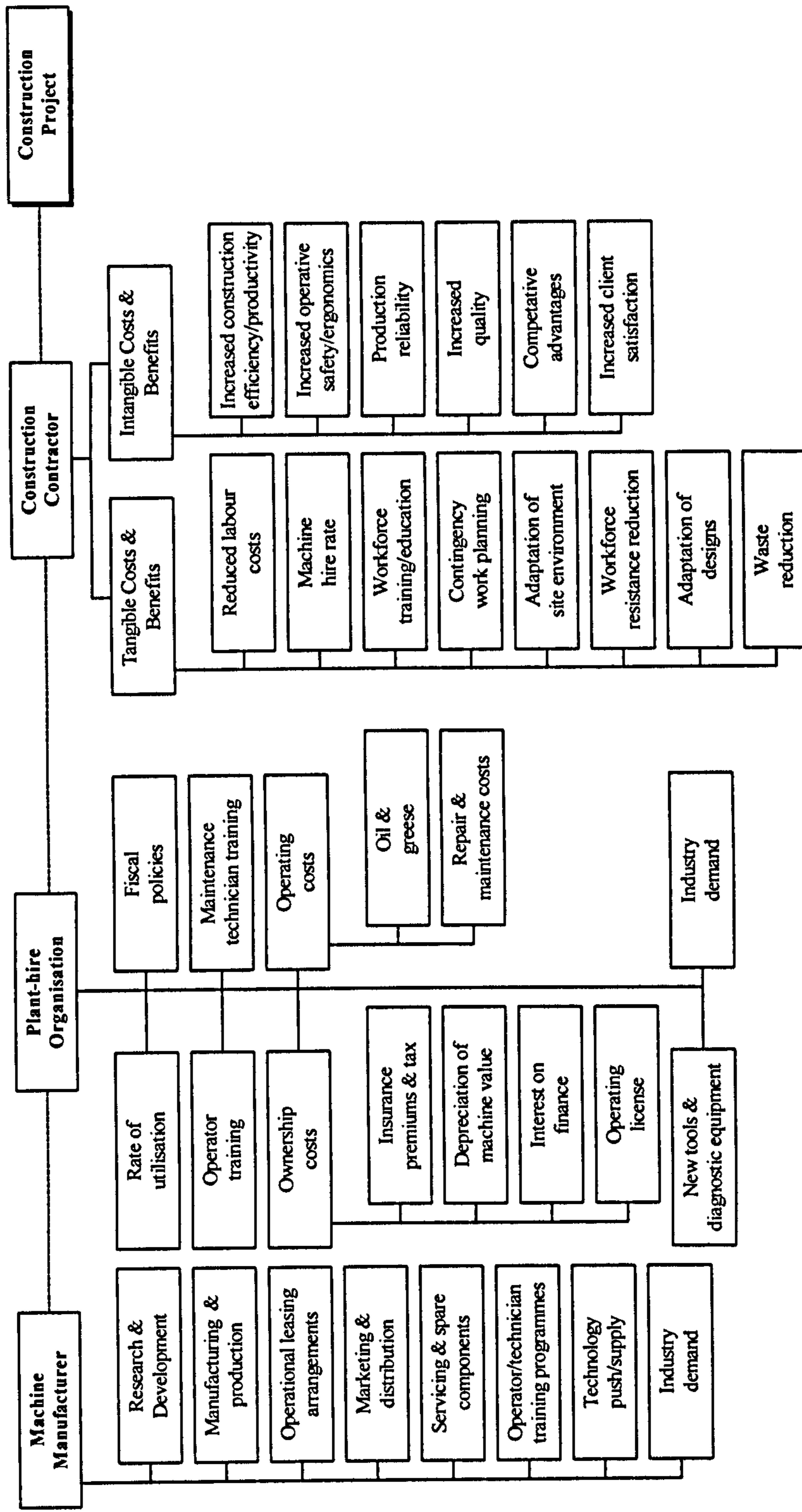


Figure 4.5 Segregated construction mechatronics economic valuation model

Industrial Sector	1992	1993	1994	1995	1996	1997	1998	1999	2000
Agriculture, hunting, forestry and fishing	9919	10544	10616	11766	11735	10145	9628	9460	8912
Total mining and quarrying	13418	13526	14788	16369	19768	18115	15678	17091	24244
Total manufacturing	115891	120989	130767	139789	146078	152304	153268	152653	155531
Construction	30020	29166	31216	33006	34587	36878	39017	41142	43287
Service industries	362259	384965	405194	423393	451171	487107	527761	558671	583407
All industries	546434	575461	608740	639908	679620	720692	761318	795025	831053
<i>Construction as a % of all industries</i>	<i>5.494</i>	<i>5.068</i>	<i>5.128</i>	<i>5.158</i>	<i>5.089</i>	<i>5.117</i>	<i>5.125</i>	<i>5.175</i>	<i>5.209</i>

Table 4.1: Gross value added by industry at current basic prices (£ million)

Source: The United Kingdom National Accounts 2001

Fiscal Year	1992	1993	1994	1995	1996	1997	1998	1999	2000
Private Sector									
New dwellings	17311	18353	19076	18860	19607	20824	20967	20472	21001
Buildings & Structures	19288	18018	18018	18023	19776	23802	25731	27748	27524
Total Construction Costs	36599	36371	37094	36883	39383	44626	46698	48220	48525
Total Cap. Form. Costs	82917	82261	92631	97616	106815	117576	135127	136369	142635
Construction as a % Total of Cap. Form Costs	44.14	44.21	40.04	37.78	36.87	37.96	34.56	35.36	34.02
Public Sector (non-financial)									
New dwellings	185	169	150	162	147	119	46	10	5
Buildings & Structures	3993	4391	3847	3781	3154	2508	2225	2317	2427
Total Construction Costs	4178	4560	3997	3943	3301	2627	2271	2327	2432
Total Cap. Form. Costs	5863	5932	6031	5776	5014	4379	4148	4389	4348
Construction as a % Total of Cap. Form Costs	71.26	76.87	66.27	68.27	65.84	59.99	54.75	53.02	55.93
<i>Construction as a % of both sectors</i>	<i>45.93</i>	<i>46.41</i>	<i>41.65</i>	<i>39.49</i>	<i>38.17</i>	<i>38.75</i>	<i>35.16</i>	<i>35.91</i>	<i>34.67</i>

Table 4.2: UK construction industry contribution to total gross domestic fixed capital formation

Source: United Kingdom National Accounts 2001

Industrial Sector	1995	1996	1997	1998	1999	2000
Agriculture & fishing	565	578	580	529	498	513
Energy & water	253	237	234	222	205	196
Manufacturing	4470	4465	4494	4449	4288	4138
Construction	1766	1737	1821	1828	1811	1852
Distribution, hotels & restaurants	6275	6366	6586	6649	6708	6797
Transport & communications	1569	1606	1600	1674	1754	1815
Finance & business services	4702	4761	5040	5207	5410	5430
Public admin., education and health	6424	6476	6400	6490	6646	6701
Other services	1478	1576	1626	1609	1719	1722
Total jobs	27501	27803	28382	28656	29041	29164
<i>Construction as a % of total</i>	<i>6.422</i>	<i>6.248</i>	<i>6.416</i>	<i>6.379</i>	<i>6.236</i>	<i>6.350</i>

Table 4.3: Employment by industrial sector (thousands)

Source: Labour Market Trends, The Office of National Statistics 2001

	1995	1996	1997	1998	1999	2000
	Construction					
Employment (thousands)	1766	1737	1821	1828	1811	1852
Total output at basic prices (£ million)	86139	90622	96756	103470	109619	115788
Output per employee (£)	48776.33	52171.56	53133.44	56602.84	60529.54	62520.52
	Manufacturing					
Employment (thousands)	4470	4465	4494	4449	4288	4138
Total output at basic prices (£ million)	382455	398448	408856	404764	402283	403299
Output per employee (£)	85560.40	89238.07	90978.19	90978.65	93816.00	97462.30

Table 4.4 Comparison of construction and manufacturing labour productivity

Source: Office of National Statistics 2001

Industrial Sector	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Chemicals	707	720	721	689	701	627	680	688	718	682
Fabricated metals	48	63	72	72	100	91	88	90	70	73
Machinery & equipment	490	517	593	689	583	577	622	640	642	703
Construction	19	15	11	11	8	8	38	39	41	34
Total (all industries)	8135	8489	9069	9204	9254	9431	9680	10261	11302	11510
<i>Machinery as a % of total</i>	6.023%	6.090%	6.539%	7.486%	6.300%	6.118%	6.426%	6.237%	5.680%	6.108%
<i>Construction as a % of total</i>	0.234%	0.177%	0.121%	0.120%	0.086%	0.085%	0.393%	0.380%	0.363%	0.295%

Table 4.5 UK business expenditure on R&D by industrial sector (£ million)

Source: Office of National Statistics 2001

Research Organisation	Objectives	Annual Government Funding
Department of Trade and Industry - DTI (formerly DETR)	Encouraging national and international competitiveness and health of industry. Improving the ability of the industry to harness the benefits of science and technology	£15 to £18 million
Department of Transport, Local Government and the Regions - DTLR (formerly DETR)	Protecting and enhancing issues of public interest, including production of building regulations. Regulations cover building design, construction and energy efficiency. Support for testing and development of materials.	£6 million
Engineering and Physical Sciences Research Council - EPSRC	Supporting the engineering and physical science research base, including engineering and production management	£39 million (current EPSRC support in construction and general civil engineering sectors)
Economic and Social Research Council - ESRC	Funds research of relevance to project management and economic geography (e.g. cities and urban development)	£2-£3 million

Table 4.6 UK public construction research organisations

Source: Fairclough 2002 and EPSRC

Research Organisation	Amount (£'million)*	Funding (%)
BRE	79.4	63.9
BSRIA	5.0	4.0
CIRIA	4.5	3.5
TRADA Technology	3.5	2.9
HR Wallingford	2.5	2.0
FBE Management	1.9	1.5
Steel Construction Institute	1.9	1.5
BRE Sctolab	1.7	1.3
Others	23.8	19.2

*Total funding received since July 1997

Table 4.7 Total DTI/DTLR funding by organisation

Source: Fairclough 2002

Research Programme/ Funding Body	Collaborating organisations	Project Description
Advanced Robotics Programme (DIT)	<ol style="list-style-type: none"> 1. Lilley Construction (lead), North-West Water Ltd., Moog Controls, James Howden Ltd. & ERA Technology 2. Caledonian Mining Company Ltd., Moog Controls, British Coal and Cambridge University 3. Taylor Woodrow, WS Atkins, Tirfor Ltd., National Engineering Laboratory, Lancaster and Reading University 	<ol style="list-style-type: none"> 1. Tunnelling field trials – robotic systems for segment erection, grouting and real-time machine condition monitoring. 2. Replacing discontinuous cutting and roof support systems with a continuous system. Temporary roof support system that ‘walks’ in pace with cutting machine, provided with a sensor driven control system for semi-autonomous tunnelling within a coal seam 3. Wall climbing robot with manipulator arm. Delayed for financial reasons.
Science and Engineering Research Council	<p>City University, London</p> <p>Lancaster University Lancaster University Lancaster University and Stent Foundations Ltd.</p>	<p>Masonry construction robot cell. A gantry type robot, which operates the grippers, material conveyor and laser beacon.</p> <p>Robot excavator – LUCIE. Starlifter Pile Production Innovation Project (P-PIP)</p>
Innovative Manufacturing Initiative	<p>University of Wales College of Cardiff Dr Wing, Imperial College, London</p>	<p>Soil stabilising machine using soil nailing for embankments and cuttings Futurehome</p>

Table 4.8 Summary of UK construction mechatronics R&D projects

Industry Sector	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Total Government	25,748	28,657	32,334	34,208	33,255	35,199	34,577	32,964	33,430	31,790	31,200	29,390
Total Private Sector	55,692	53,747	51,637	47,485	45,498	43,818	48,230	42,226	37,340	38,500	39,160	37,740
<i>Building Government</i>	4,601	5,639	6,363	6,697	6,474	5,667	5,713	5,423	4,980	4,690	4,510	3,800
<i>Building Private Sector</i>	47,631	45,077	42,712	38,610	37,456	35,322	40,062	34,464	29,940	29,970	30,070	28,820
Civil Engineering Government	21,147	23,018	25,971	27,512	26,781	29,531	28,865	27,541	28,450	27,100	26,690	25,590
Civil Engineering Private Sector	8,061	8,670	8,925	8,875	8,042	8,496	8,169	7,763	7,400	8,530	9,080	8,920

Table 4.9 Japanese construction investment, 1990 to 2001

Source: Japanese Ministry of Land, Infrastructure and Transport, 2001

Company	Japan Fiscal Year			
	1995	1996	1997	1998
Taisei Corporation	12.6	12.144	11.9	10.1
% of annual sales	0.73%	0.63%	0.54%	0.60%
Kajima Corporation	22.711	20.477	20.285	19.315
% of annual sales	1.08%	1.16%	0.96%	0.99%
Shimizu Corporation	13.498	12.697	11.579	11.388
% of annual sales	0.65%	0.70%	0.67%	0.65%
Obayashi Corporation	13.6	12.699	11.971	11.877
% of annual sales	0.96%	1.02%	0.78%	0.80%
Kumagai Gumi	3.5	3.7	3.89	3.341
% of annual sales	0.38	0.34	0.37%	0.29%
Toda Corporation	1.358	1.322	1.25	1.163
% of annual sales	0.21%	0.21%	0.18%	0.17%

Unit=¥1 Billion (1,000,000,000) = £5.5 million (£1=¥182)

Table 4.10 Big-Six Japanese general contractors research and development expenditure, 1995 to 1999

Source: annual reports

	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00
	Fatal and major							
Construction	238	223	228	232	411	388	407	392
All industries	82	80	81	78	128	129	123	118
	All reported injuries							
Construction	1516	1351	1368	1262	1490	1354	1271	1290
All industries	751	721	738	685	709	718	690	665

Table 4.11 Injuries to employees, construction vs all industries (rates per 100,000 employees)

Source: Construction Statistics Annual 2001

CHAPTER 5

THE ANALYSIS OF CONSTRUCTION AUTOMATION INVESTMENT RISK

5.1 Introduction

Risk denotes that the decision-maker is uncertain as to the precise outcomes of a decision, which involves the possibility of undesirable consequences or loss (Ho & Pike 1991). Lifson (1982) defines risk as the uncertainty associated with estimates of outcomes. Risk here means, therefore, that there is a chance that results could be better than expected as well as worse than expected. Flanagan and Norman (1993) conclude that the majority of risks arise from matters where there is a lack of information. The application of any risk analysis technique requires that the uncertain data be given a range of different values (Thompson & Perry 1992). The term risk analysis can be defined as a means for managers to contemplate and confront the future uncertain environment in which they operate (Hertz 1983). Figure 5.1 defines the risk analysis process.

Within an investment appraisal context, risk may be defined as the adverse exposure to uncertainty. Uncertainty may be defined as the randomness of the external environment, which is fixed, constant and can not be altered by managers. The line of business within which an organisation operates, the cost structure of the organisation, its operations and the nature of contracts to obtain inputs and sell outputs determines exposure to uncertainty.

Construction automation investment decisions are inherently complex due to the extensive range of economic, financial, technical and managerial uncertainties. The complexity of the decision is mainly contributed to by the prototype and revolutionary nature of such

technologies. Therefore, there is limited historical data regarding the implementation of the existing technologies. In existing appraisal methodologies the investment cost and benefit parameters are normally assumed to be discrete estimates, which neglect the possibility of variation. Selected investment decision parameters have been considered in a speculative manner, such as hours utilised and maintenance costs. Furthermore, the DCF decision criteria do not incorporate a measure of investment risk. These assumptions render the predicted results no better than decisions based upon managerial intuition.

The existing investment appraisal methodologies are idealised representations of reality and therefore imperfect representations of the actual situation. Imprecision concerning cash flow estimation originates from undetermined ownership and operating expenditures. Subjective estimates have to be obtained when determining the parameters to be used in any construction automation investment model since such technologies are often prototypes or have not been utilised enough to provide adequate historical implementation data.

Tangible uncertainties, whether they are either costs or benefits, may be assessed in statistical terms. The distribution of new technology investment risk has generally been skewed towards the end-user (contractor) assuming responsibility for most of the risks associated with the innovative plant. The significance of such uncertainties, which must be attributed to the appropriate construction parties, can be evaluated using risk analysis. Furthermore, non-tangible benefits substantially contribute to the economic value of construction automation and must be considered using qualitative risk analysis.

The term 'risk analysis' originated with Hertz (1964). Risk analysis aims to aid executives in key capital investment decisions by furnishing them with a realistic measurement of embodied risk. Rather than predicting discrete estimates for inputs to investment decision

models, it was proposed that probability distributions replace discrete estimates and that these input distributions are sampled to generate an output risk profile for the chosen performance criterion. Risk analysis will provide decision-makers with awareness of the risks associated with the investments return; insight into costs or savings sensitive to overall profitability; and assistance in making a more effective investment decision.

5.2 Financial risk analysis methodology

Exposure to risk is a fundamental aspect of construction related operations. There are risks that are unavoidable, while a selection of risks must be managed. Risk management is the process of identifying and evaluating the trade-off between risk and expected return, and choosing the appropriate course of action (Pike & Neale 1999). The effective management of risk may add value to an organisation through improved financial performance and increased profitability.

The essence of financial risk analysis is that it attempts to encompass all feasible alternatives and to analyse the various outcomes of an investment decision. The use of financial risk analysis provides an insight into the situation that may occur if the uncertain variables realise their down-side potential. Probabilistic risk analysis is a powerful tool for investigating investment decisions, which rely upon predictions of future costs and revenues. Monte Carlo simulation assumes that discrete investment appraisal input parameters are replaced with probability density functions, which better describe the uncertainty associated with these uncertain variables.

The construction industry relies heavily on well-established technologies, operates within a competitive and harsh financial environment and is preoccupied with financial risk (Baker *et al* 1999). Exploration of the financial risk associated with automated construction

technology is necessary to assist quantification and understanding of investment and utilisation risk. Through improved awareness of the associated financial risk, automated construction technology may be more widely adopted within the UK construction sector. It has been stated that risk analysis encourages managers to initiate, sponsor and approve investment proposals as it improves their forecasting accuracy and decision confidence (Ho & Pike 1992). In this chapter, a generic construction automation financial risk analysis model is proposed in conjunction with recommendations for appropriate input parameters and probability distributions.

5.3 Financial appraisal methodology

Two financial appraisal techniques namely the Warszawski (1999) and McCaffer (1995) methods were modified and combined to produce a financial appraisal methodology that values an automated construction system based upon its potential value to a plant-hire organisation. Monte Carlo simulation is then used to perform risk analysis on a hypothetical construction automation investment. A brief derivation of the Warszawski method is presented in Section 5.3.1 and the McCaffer method is discussed in Section 5.3.2. Finally, the author's construction automation plant hire valuation model is described in Section 5.3.3.

5.3.1 Warszawski: assessment of economic feasibility

Warszawski (1999) examined the costs and benefits of employing a multipurpose interior-finishing robot. In this method, the total cost of a construction robot is divided into three component costs. These are capital costs, direct costs and transfer costs.

The total cost, C_r , is calculated from:

$$C_r = \frac{C_{rs}}{(H \times Q_h)} + \frac{C_d}{Q_h} + C_t + \frac{C_m}{(H \times Q_h)} \quad 5.1$$

Where:

$$C_m = (0.1 \times P) + (0.06H \times C_l) \quad 5.2$$

$$C_{rs} = \left((P - L) \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right) \right) + (L \times i) \quad 5.3$$

$$C_d = C_o + C_e + (c_{mt} \times Q_h) + (c_x \times Q_h) \quad 5.4$$

$$C_t = \frac{C_s}{Q_s} + \frac{C_{lc}}{Q_{lc}} + \frac{C_w}{Q_w} \quad 5.5$$

where P is the initial capital investment;
 C_m is the annual maintenance costs;
 C_t is the cost of transfers per unit;
 i is the interest rate;
 n is the economic life of the machine;
 C_r is the total cost of robotised work per unit
 C_{rs} is the capital cost of the system per annum
 H is the hours employed per year
 C_s is the average set-up cost on-site

Q_s	is the average number of work units per station
Q_h	is the output of the system per hour
C_d	is the direct cost per hour
L	is the terminal value of the system
C_o	is the cost of operator per hour
C_e	is the cost of resources per hour
C_{mt}	is the cost of materials per work unit
C_x	is the cost of auxiliary labour per work unit
C_{lc}	is the average transfer cost (floors/buildings)
Q_{lc}	is the average work units per location
C_w	is the travelling cost between work stations
Q_w	is the average work units per station

Limitations of this methodology include:

- the use of discrete estimations for the associated costs and benefits, which ignore down-side risk and up-side potential of the investment;
- the use of a single discount rate, instead of a rate which reflects project risk may lead to the rejection of low-risk and low-return projects which may be of strategic value to the organisation;
- the assumption that repair and maintenance costs will remain constant over the functional life of the machine;
- the assumption that the end user, i.e. the contractor, is responsible for the operating and ownership costs of the machine; and
- the intermediary role of plant-hire organisations in the adoption and use of such expensive and utilisation rate dependent machines has been neglected.

The nature of the estimates used for cost and benefit analysis are discrete and do not incorporate any tolerances for possible cash flow uncertainty. Furthermore, the use of single discount rate may not provide a true indication of the potential investment value. Furthermore, the underlying assumption that the end-users (i.e. the contractors) would be responsible for the ownership and operating costs has neglected the possibility of the plant-hire industry being actively involved in the use of automated construction technologies. In this thesis, the valuation model was adapted to account for the above limitations.

5.3.2 Harris & McCaffer: determination of marginal hire rates

Utilising the methodology described by Harris and McCaffer (1995), marginal hire rates (MHR) may be calculated using the expression:

$$\text{MHR} = \frac{OW + OP}{h} \quad 5.6$$

where:

$$OW = I + L + D + A \quad 5.7$$

$$OP = F + O + R \quad 5.8$$

where I is the annual insurance costs;
 L is the cost of licences & taxes;
 F is the cost of fuel (electricity or diesel);
 O is the cost of oil & grease;
 D is the annual depreciation;
 A is the uniform end-of-series payment

R is the cost of repairs and maintenance, and
 h is the hours utilised per annum.

Using the above calculations, a profit and overhead premium (10% of marginal hourly hire rate) may then be added as follows:

$$HR_{+premium} = \left(\frac{OW + OP}{h} \right) \times 1.10 \quad 5.9$$

The annual cash flows for the determination of the NPV of the future cash flows are calculated using Equation 5.10. The final year cash flow is calculated by adding the resale value to the cash flow derived from Equation 5.10.

$$Annual\ cash\ flow = \left(h \times HR_{+premium} \right) - (OW + OP) \quad 5.10$$

The above calculations have been adapted and modified to incorporate the additional costs associated with the use of automated construction technologies. The following section describes how both of these methodologies have been adapted and combined to produce a generic appraisal methodology for plant-hire organisations considering the purchase and use of construction mechatronics technologies.

5.3.3 Plant-hire valuation model

Fluctuation in demand for contractors' services is a considerable disincentive for substantial investment in new technologies (Dodgson & Rothwell 1994). Contractors aim to minimise their fixed capital locked into production by hiring or leasing expensive plant and equipment. The construction industry avoids working practices that demand substantial investment in plant and machinery. Construction projects are unique and

specialist plant with skilled operators may only be required for limited time periods. The plant-hire industry meets the requirements of contractors and facilitates access to plant and operators without exposure to ownership and operating costs. With regards to civil engineering operations, the work often involves the use of expensive plant, which, to be cost effective, has to be utilised to its utmost.

The following appraisal methodology is constructed upon the premise that the most economically viable method of employing automation and robotics onto construction and civil engineering projects would be through a plant hire organisation purchasing the machine and, subsequently, hiring that machine to construction and civil engineering contractors.

The net present value (NPV) investment criterion is used to measure the profitability of the hypothetical construction automation investment opportunity. The NPV is expressed as:

$$NPV = \sum_{t=0}^n F_t (1+i)^{-t} \quad 5.11$$

where F_t = annual cash flow in time period t ; i = interest rate or cost of capital in fiscal year t ; and $t = 0, 1, 2, \dots, n$. The NPV is a function of several uncertain cash flow variables. Further to determining an NPV risk profile, the investment risk can be estimated as the probability of the NPV being less than the target value, i.e. greater than zero. The composition of each of these uncertain variables is described in the remainder of this section. Table 5.1 provides descriptions, symbols and standard units for the cost components and input variables used within the financial risk analysis model.

Assuming that the economic life of the system is five fiscal years, the annual cash flows may be expressed as:

$$F_0 = (HR - (P + OW + OP)) \times n_{systems} \quad 5.12$$

$$F_1 = (HR - (OW + OP)) \times n_{systems} \quad 5.13$$

In the final year of the machines functional life, the residual value of the system may be accounted for using the expression:

$$F_5 = (HR + S_r - (OW + OP)) \times n_{systems} \quad 5.14$$

The ownership costs may be expressed as:

$$OW = (I + l + D + A) \quad 5.15$$

The cost of operating licenses and insurance premiums is dependant upon the nature of the automated plant and the activities which it will undertake. These costs are unknown at the time the investment decision is made and may be subject to uncertainty. Automated manufacturing systems require inspection and operating certificates in order to ensure their safe operation. Automated construction systems may also be subject to similar operating restrictions.

Figure 5.2 compares the alternative methods of depreciation with the annual rate of depreciation plotted against the functional life, in years, of the machine. The four alternative methods are applied to the example of an asset having an initial cost of £100,000

and a residual value of £10,000 after a working life of 5 years. The declining balance method is used due to the machine being heavily written down in the early years and depreciation decreasing with increasing age. This is appropriate for construction plant and machinery due to the repair and maintenance costs being low when the machine is new, but increasing with age and operating hours (Harris & McCaffer 1995). Furthermore, this pattern of depreciation tends to follow the pattern of an asset's ability to contribute to income arising from its use (Pilcher 1992).

The declining balance assumes that a fixed percentage of the book value of the machine is written off annually. The ratio of the amount of depreciation for any year to the book value of the asset at the beginning of that year is constant over the economic life of the machine. The declining balance depreciation is calculated as a percentage using the expression:

$$d = 1 - \sqrt[n]{\frac{S_r}{P}} \quad 5.16$$

Assuming that the purchase of any machines will be financed with borrowed funds, the cost of the annual loan repayments was assumed to be a uniform end of series payment, and expressed as:

$$A = (P - S_r) \times \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad 5.17$$

The bracketed factor is known as the uniform series capital recovery factor (Pilcher 1992). A is the uniform end-of-period payment necessary to repay a debt in n periods if the interest

rate is i . P is the initial purchase price of the machine (or principle sum) and S_{scrap} is the residual or scrap value of the machine following realisation of the machine's economic life. The operating costs may be expressed as:

$$OP = (F + R_m + (S_s \times n_{sites}) + T) + ((L_{op} \times n_{op}) \times H) \quad 5.18$$

Consumable resources, F , include those necessary for the reliable operation of the system and include oil, grease and tyres or tracks (depending upon configuration of locomotive base).

Scheduled maintenance has been valued as a percentage of the initial purchase price of the system. It is assumed that the annual cost of scheduled maintenance will grow exponentially as a function of the operational life of the machine. This assumption infers that as the machine wears with age and use, the cost of maintenance will increase. Routine maintenance, undertaken on a daily basis by the machine operator, is incorporated as a function of the daily maintenance time multiplied by the number of days utilised per annum. The cost of maintenance may be expressed as:

$$R_m = (\Phi.P) e^{(\theta_m \cdot (n-1))} + \left[\left(M_t \cdot \frac{H_{yr}}{H_{day}} \right) L_{op} \right] \quad 5.19$$

where Φ is the cost of scheduled maintenance as a percentage value of the initial machine purchase price;

θ_m is the exponential maintenance cost growth factor as a function of the functional life of the machine, and

M_t represents the daily maintenance time period.

Figure 5.3 provides a graphical comparison of the initial first year repair and maintenance costs ($\Phi = 10\%$, 5%) and a comparison of the effect of varying the exponential rate of scheduled maintenance cost growth ($\theta = 0.10$, 0.15 , and 0.20)

Transferring a construction robot between construction projects and between work-stations on each of the projects will contribute significantly to the overall operating costs. Within the proposed model, the number of inter-site transfers for routine maintenance and the number of intra-site transfers between work stations will present significant costs which may be expressed as:

$$T = \left(n_{transfers} \times C_{transfer} \right) + \left(n_{stations} \times \left(L_{op} \times H_{station} \right) \right) \quad 5.20$$

The following assumptions must be considered when valuing potential construction automation investment opportunities using the risk analysis model:

- the technology is being valued from the value derived from hiring the system on a hourly basis to construction and civil engineering contractors;
- the hourly hire rate remains constant, in real terms, over the functional life of the machine, despite variations in the ownership and operating costs;
- it is assumed that the cost of maintenance and repairs will follow an estimated exponential growth pattern to account for the increasing cost of maintenance as the machine wears with use;
- there are no variations to the mean cost of capital over the economic life of the machine;

- depreciation is calculated on a declining balance basis to reflect the increase in repairs and maintenance costs as the asset ages;
- the rate of corporation tax is 30%, and
- writing down allowances are calculated as 25% of the written down value of the asset on a declining balance basis.

The following section describes the sources of risk inherent within a construction automation investment. The sources of risk are categorised and described.

5.4 Sources of risk

From a general perspective, the risk associated with construction automation investment opportunities may be defined as a function of five categories. Figure 5.4 presents a taxonomy of construction automation investment risk. Economic risk is dependent upon the supply and demand of automated construction technology, the labour markets and the availability of cheap affordable labour and the functional life of the machine. Technological risk arises from uncertainty relating to the reliability of the machine and its mechanical components. Despite any innovative technology being extensively tried and tested in laboratory conditions, the use of automated technology within a construction project environment may present significant challenges to mechanical components, which were initially designed for operating within manufacturing environments.

Financial risk may be generally subdivided into systematic (market) and unsystematic (specific) risk. Both sources of financial risk present significant influence upon the operations of a construction related organisation and must be considered in any study of risk. However, other sources of financial risk include the machine operating and ownership

costs, machine acquisition costs, auxiliary labour costs and the uncertainty surrounding potential hire revenues.

Organisational risk may be related to industrial relations and the requirements for employee and managerial training. Finally, operational risk relates to the efficient operation of a machine and its ability to undertake the required task within the predetermined schedule and meet the desired construction specification.

The following sub-sections present descriptions of economic, technological, financial, organisational and operational risk and the means by which they may affect a construction automation related investment opportunity. Investigations in this study focus predominantly on financial risk.

5.4.1 Economic risk

Economic risk relates to the demand for automated equipment from contractors, which is also related to the supply of such technologies from international machine manufacturers. Furthermore, issues relating to the supply of cheap and affordable labour may deem expensive automated technology uneconomical. The UK construction labour markets and the existing pay levels may provide an important source of economic uncertainty. Finally, the functional life of a machine will have a significant impact upon the economic viability of the investment.

5.4.2 Technological risk

Within the context of this study, technological risk relates to adverse exposure to uncertainty relating to the efficient functioning of a machine within a construction project

environment. Technological risk may incorporate the availability of suitable resources to operate and maintain the machine. These resources may include suitably qualified and experienced operators and maintenance technicians. However, if a maintenance contract is undertaken with a manufacturer, this source of technological risk may be irrelevant.

5.4.3 Financial risk

For a plant hire organisation considering investment in automated construction technology, financial risk is of prime importance. Costs relating to the ownership and operation of a machine will present significant uncertainty and adverse exposure to these uncertainties may generate significant risk. Significant operating risks include the possibility of under utilisation, high repair and maintenance costs, high transfer costs, the cost of operators salary, high rates of insurance and high site set-up costs. Furthermore, there may be significant uncertainty surrounding the potential hire revenue from such innovative technology (relating to technology demand), the initial machine acquisition costs and the costs associated with any auxiliary labour. The following sub-sections describe how financial risk may be further separated into market and specific risk components.

Systematic risk

Systematic risk refers to risk, which can not be eliminated through diversification and stems from cyclical market fluctuations. Systematic risk is often known as market risk, since it is a function of the general environmental conditions that affect the industry as a whole. It constitutes the risk, which reflects the relationship of its fluctuations to those of the sector in which the firm is operating. In relation to financial securities, the higher a securities beta (β) coefficient, the higher it's exposure to systematic risk, and therefore the higher the risk premium and the expected return on the security.

Factors of particular interest to the construction industry include unanticipated increases in inflation or interest rates, labour and skill shortages and economic downturn or recession (Farid *et al* 1989). The cyclical nature of the construction sector is a major factor in market risk, since general economic trends will have a greater impact upon cyclical than non-cyclical industries. Reimann (1990) comments that exposure to market risk can be reduced through developing an increase in market power. He concludes that corporate strategies may be instrumental in reducing market risk by improving business unit capabilities for attaining sustainable competitive advantages. The effects of market risk may be accounted for by using the CAPM in the derivation of the cost of capital. However, there has been considerable debate over the appropriateness of the CAPM for asset valuation within the construction industry.

Unsystematic risk

Sources of unsystematic risk, often known as specific risk, in construction include the weather, unexpected work conditions, strikes and in particular financial difficulties (Farid *et al* 1989). Furthermore, the efficiency of directors and site level management presents an important source of specific risk in construction projects. Reimann (1990) also includes technological changes as a potential source of business-specific risk. It is difficult to measure these risks for both stock market quoted and unquoted private firms. However, these risks are evident within every construction-related organisation.

5.4.4 Organisational risk

New technology requires interaction with the human resource strategies of the firm. There may be a requirement for complementary changes in the skills of employees and managers, to accommodate automated technologies. Furthermore, there may be complementary

changes to working practices and modes of organisation, which are not compatible with the new technology.

Under certain circumstances, construction mechatronics technologies may be associated with the decline of certain occupations. Concerning industrial relations, Trade Unions may be concerned with company investment strategies, the precise equipment which will be used, manning levels and working practices, pay levels, the selection and training of workers and working conditions (health and safety).

5.4.5 Operational risk

Within the context of construction automation investment, operational risk relates to factors specifically related to the operation of a machine within a construction project environment. Issues of importance include the safe operation of the machine, i.e. all working areas are suitably cordoned off to ensure that human operatives do not pass within the machines zone of influence. The productivity of the machine must be continuous to ensure that schedules are maintained. Concerning quality, the machine must produce a finished product of satisfactory quality in relation to the design specifications. The site conditions will play a major role in the machine's ability to remain productive and provide appropriate quality standards. Appropriate security must be ensured and all materials, which may be critical to the productivity and quality of the automated system, must be free from damage and stored in an appropriate location.

5.5 Probability distributions for cash flow estimation

Probability distributions may be used when considering future cash flow estimates, which are uncertain and may have more than one possible outcome. In an investment scenario

only one of the estimated outcomes will occur. However, predicting the exact outcome is not possible. Probabilities may be expressed as decimal fractions or as percentages. A probability of 1 infers that an event is certain to occur. Probabilities are usually determined using empirical data. However, in the absence of appropriate historical data, subjective probabilities may be determined from interviewing industry experts.

The following sections describe the relevant probability distribution functions described in the literature for modelling cash flows. The need for subjective estimation of probabilities when examining construction automation investment is discussed. The appropriate profitability measure and the probability distributions used in the risk analysis model are described.

5.5.1 Appropriate probability distributions

There has been considerable debate over the appropriateness of specific probability distributions in modelling construction project costs. The choice of input distribution is not based upon a search for the 'true' distribution for the variable in question, but on the objective of modelling the estimator's perception of the range and probability of the likely outcomes (Raftery 1994).

Simple probability distributions are advocated in the absence of statistical data. Triangular, rectangular and trapezoidal distributions are useful for representing situations where there is no evidence that one particular value is any more likely to occur than another within the prescribed range (Perry & Hayes 1985). Raftery (1994) emphasised the extensive use of uniform, triangular, trapezoidal, step-rectangular and discrete probability distributions in the construction of robust models of risk for oil and gas exploration and large defence

projects. In the evaluation of risk in major capital projects, Hull (1977) advocated the use of triangular and uniform probability distributions in describing the uncertainty associated with market size, market growth rate, product selling price, initial investment, life of the proposed investment, operating costs, fixed costs and residual value.

Chau (1995) investigated the validity of the triangular distribution in the estimation of construction cost data. He explained that the triangular distribution might lead to an over estimation in the probability of exceeding the most likely estimate. The p.d.f. of a construction project input variable is skewed with a long thin tail to the right of the distribution. This results because high construction costs are often the result of a combination of unexpected events, for which the probability of occurrence is small. The tail to the right of the appropriate distribution should be thinner than that estimated by the triangular distribution. A theoretical lower boundary exists, which is determined by the minimum amount of resources required to construct the structure, but a theoretical upper limit does not exist. Therefore, p.d.f's should have a long thin tail to the right (i.e. be positively skewed). As construction costs have been shown to be positively skewed, symmetrical distributions are ruled out. However, he concluded that the triangular p.d.f assumption was insignificant when compared with the error inherent in imprecise subjective data. Wall (1997) showed that further to a comparison of the beta and log-normal distributions in describing elemental project cost data using the chi-squared (χ^2) goodness of fit test, the log-normal distribution was superior to the beta distribution in representing cost data.

Subsequently, the use of alternative probability distributions will be examined. However, the determination of goodness-of-fit using statistical tests is not possible due to the existing

lack of construction automation implementation data. The use of subjective estimation is considered in the following section.

5.5.2 Subjective estimation

The continuously dynamic nature of the economy and the distinctive nature of all construction projects, in which decisions are often unique and objective estimations from historical information impossible to obtain (Flanagan & Norman 1993). The selection of input probability distributions is based upon the estimator's perception of the range of values and the probability of these outcomes arising.

If objective data is not available for determining probability distributions for inputs to a risk analysis model, then subjective data, based upon managerial judgement, may be utilised (Raftery 1994). For subjective probabilities to be used effectively as inputs to risk analyses they must be accurate, calibrated and coherent (Ranasinghe & Russell 1993). An expert is calibrated when an event is assigned a probability and the actual occurrence of that event is close to the estimated probability. The subjective estimates are coherent if they are compatible with the probability axioms.

The logical technique for investigating the p.d.f.'s of input parameters would be to collect historical data from similar projects (i.e. cases where the machine has been utilised on-site), assume an appropriate p.d.f.'s and perform a goodness of fit test to evaluate the hypothesis (Touran & Wiser 1992). Outcomes such as costs and profits often cannot be investigated completely, and, furthermore, must be estimated before the system involved is in existence (Lifson 1982). It is often easier to accurately guess a range rather than a single value (Hertz 1983). Subjective probability distributions are generally based upon estimator's previous

experience and, therefore, provide orderly consistent opinion (Lifson 1982). However, concerning construction automation investment, there is considerable difficulty associated with obtaining data from contractors and plant-hire organisations who have no experience with such technology. Even if sufficient historical data exists, the problem still exists of how to project those figures into the future (Woodward 1997). For many uncertainties in construction there is insufficient objective data upon which probabilities of occurrence can be calculated.

Perry and Hayes (1985) conclude that subjectivity is present in all aspects of construction estimating and that open recognition and analysis of risk and uncertainty will provide better and more realistic information. Subjective estimates are not perfect substitutes for objective data (Chau 1997). However, attention must be drawn to the need to update cost information and cash flow data in addition to site trials or work studies conducted during the implementation of automated construction technology.

5.5.3 Profitability measurement criteria

In order to analyse the financial risk associated with construction automation investment opportunities, a suitable profitability criterion must be selected. Discounted cash flow valuation techniques provide a suitable means of measuring the profitability of an investment scenario. The NPV technique has been suggested as an appropriate measure of profitability to be used in conjunction with probabilistic risk analysis (Wagle 1967; Eilon & Fowkes 1973; Hull 1977; Hull 1980; Hertz 1983; Jaafari 1988; Thompson & Perry 1992; Harris & McCaffer 1995; Javid *et al* 2000).

Hertz (1983) concludes that the NPV criterion has advantages over other profitability measures because it provided an unambiguous measure of the value of the incremental project for the firm. The spread or variability of an NPV probability distribution may be measured using the standard deviation of the investment return. The chosen performance criterion for this research is NPV. Since the objective of the firm is to maximise shareholder wealth, then managers entrusted with these funds should not invest in projects unless the expected returns exceed those available to shareholders in the capital markets. NPV results predict the likely net effect of a project upon the market value of the firm.

The net present value (NPV) of an investment is the sum of the net discounted future cash flows:

$$NPV = \sum_{t=0}^n F_t (1+i)^{-t} - k \quad 5.21$$

where F_t is the projects cash flow (either positive or negative) in time t (a value from 0 to n , where n represents when the economic life of the machine expires);

k is the initial investment, and

i is the annual rate of discount or the time value of money.

The time value of money, i , is assumed to remain constant over the economic life of the machine. The NPV decision rule for project investment analysis is that if the NPV is greater than zero the project should be accepted, if less than zero the proposal should be rejected.

Standard deviation, σ , is a popular and useful measure of absolute risk. Absolute risk is the overall dispersion of possible payoffs or net present values (Hirschey & Pappas 1993). The smaller the standard deviation, the less dispersed the probability distribution and the lower the risk in absolute terms. It is assumed within the following risk analysis that the output performance criterion can only be measured in terms of standard deviation if it is normally distributed around the mean value.

Relative risk is the variation in possible returns compared with the expected payoff amount. A method for determining relative risk is to calculate the coefficient of variation. When comparing decision alternative with costs and benefits that are not approximately equal size, the coefficient of variation measures relative risk better than does the standard deviation (Hirschey & Pappas 1993).

The possibility of a negative NPV can be gauged from the area under the output probability density function that lies to the left of the line that denoted an NPV of zero. Figure 5.5 provides a graphical example of the calculation of the up-side potential of an investment opportunity. Whether such a level of risk is acceptable depends upon the risk aversion of the investment decision-maker (Smith 1994). The results of a risk analysis will allow the decision-maker to quickly appreciate the possibility of the project NPV resulting in a negative value.

5.5.4 The discrete distribution

By definition, any random variable that can take on only a finite number of values is discrete. For example, the value of the outcomes observed from a series of die throws is a discrete random variable; there are only six possible outcomes, and a probability can be

attached to each. Suppose that X is a discrete random variable and that x is one of its possible values. The probability that the random variable X takes a specific value x is denoted P_i . The discrete distribution probability density function may be expressed as:

$$f(x_i) = P_i \quad 5.22$$

The cumulative probability distribution function may be expressed as:

$$F(x) = \sum_{j=1}^i P_j \quad 5.23$$

The mean and variance of the discrete distribution may be expressed as:

$$\mu = \sum_{i=1}^n x_i P_i \quad 5.24$$

$$\sigma^2 = \sum_{i=1}^n (x_i - \bar{x})^2 P_i \quad 5.25$$

Discrete probability functions may be used to describe variables, which may only assume integer values. For example, the total number of sites per annum, the total number of work stations per site and the total number of work station transfers per site may only be quantified using integers. These variables can exhibit any value between the upper and lower limits and there is a continuous, yet discrete, scale of measurement.

5.5.5 The normal distribution

The normal distribution is a continuous probability distribution with probability density function:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(1/2)([x-\mu]/\sigma)^2} \quad 5.26$$

The graph of this function is a bell-shaped curve which is symmetrical about the mean value, μ , and the degree to which it is spread out is determined by the value of the standard deviation, σ . Approximately 68% of the area under the normal curve is within one standard deviation of the mean, 95% of the area is within 1.96 standard deviations of the mean and about 99.7% of the area within 3 standard deviations.

The probability of an observation lying between two points on a normal distribution curve is found by calculating the area under the curve between the two values. Unfortunately, it is not possible to evaluate it analytically.

$$\int_a^b \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(1/2)([x-\mu]/\sigma)^2} dx \quad 5.27$$

It is possible to convert observations from any normal distribution into equivalent values from the standard normal distribution. The standard normal distribution is a normal distribution having a mean of zero and a standard deviation of one. Probabilities from the standard normal distribution are available in standard statistics text book. To find the probabilities for a normal distribution the mean and standard deviation for each observation is transformed using the formula:

$$z = \frac{(x - \mu)}{\sigma} \quad 5.28$$

This transformation is simply a change of scale:

$$P(X \leq A) = P\left(\frac{X - \mu}{\sigma} \leq \frac{A - \mu}{\sigma}\right) \quad 5.29$$

The distribution of $(X - \mu)/\sigma$ has a mean of zero and a standard deviation of one. Thus, a transformed value, z , belongs to the standard normal distribution which can be looked up the fore mentioned statistics tables.

The normal distribution has two parameters; the mean and the standard deviation. The normal distribution can be successfully used if the decision analyst has a high level of confidence in the most likely price. If one has a high level of confidence, this infers that σ is small. Through utilising the normal distribution to describe the input variables, it is assumed that there is a high confidence level in the associated discrete cash flow estimates.

5.5.6 The triangular distribution

The triangular distribution may be utilised to describe a cash flow for which the minimum, most likely and maximum values can be estimated. Values close to the maximum and minimum are less likely to occur than the values surrounding the most likely estimate. The density function of the triangular distribution is:

$$f(x) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & \text{if } a \leq x \leq b \end{cases} \quad 5.30$$

$$f(x) = \begin{cases} \frac{2(c-x)}{(c-a)(c-b)} & \text{if } b < x \leq c \end{cases} \quad 5.31$$

where a is the minimum, b is the most likely and c is the maximum value. The mean and variance of the triangular distribution are:

$$\mu = \frac{a+b+c}{3} \quad 5.32$$

$$\sigma^2 = \frac{a^2 + b^2 + c^2 - ab - ac - bc}{18} \quad 5.33$$

The probability distribution function of the triangular distribution is:

$$F(x) = \frac{(x-a)^2}{(b-a)(c-a)} \quad \text{if } a \leq x \leq b \quad 5.34$$

$$F(x) = 1 - \frac{(c-x)^2}{(c-a)(c-b)} \quad \text{if } b < x \leq c \quad 5.35$$

The triangular distribution is widely utilised because of its ability to model uncertainty when objective data is absent.

5.5.7 The uniform distribution

The uniform distribution with a minimum and maximum value is defined by the density function:

$$f(x) = \frac{1}{a-b} \quad a \leq x \leq b \quad 5.36$$

The probability distribution function of a normal distribution may be expressed as:

$$F(x) = \frac{x-a}{b-a} \quad a \leq b \quad 5.37$$

$$a \leq x \leq b$$

The mean and variance of the uniform distribution may be expressed as:

$$\mu = \frac{a+b}{2} \quad 5.38$$

$$\sigma^2 = \frac{(b-a)^2}{12} \quad 5.39$$

The parameters a and b may be defined as the minimum and maximum values, and values between these two extreme values are equally likely to occur. The uniform distribution may be applied to cash flows where quantities vary uniformly between two values. For example, if there is no historical information regarding the repair and maintenance of an automated construction machine, the value for any expenditure relating to this unknown cost may occur.

5.6 Monte Carlo simulation

The Monte Carlo simulation (MCS) method provides solutions to a variety of mathematical problems by performing statistical sampling. The technique is named after the city of Monaco, because of the many roulette wheels, which generate random numbers for gambling purposes within the cities casinos. The development of MCS as a research tool stems from work on the first atomic bomb project during 1944. The work related to the simulation of the probabilistic problems concerning random neutron diffusion within fissionable material.

Monte Carlo sampling refers to the technique for using random or pseudo random numbers to sample from a probability distribution. Monte Carlo techniques have been applied to a variety of scientific and engineering problems involving random behaviour. Monte Carlo simulation techniques are used extensively in finance for pricing derivatives or estimating the value-at-risk of a portfolio. The Monte Carlo procedure involves drawing samples from probability distributions used to describe the input parameters of the investment appraisal

model. The cash flow is determined for each year using the sampled values and the NPV is calculated using the economic life of the machine. Finally, this process is repeated a large number of times and generates a frequency distribution for NPV. The standard deviation of the NPV indicates the level of risk incorporated within the investment decision.

In the Monte Carlo simulations presented, all or part of the input variables were generated randomly from their subjectively estimated probability distributions and were subsequently used in the determination of the investment NPV. As a result, the NPV of the hypothetical investment scenario can be described as a probability distribution. In this study, each variable was generated from either a normal, triangular, discrete and uniform distribution. It will be shown later in this chapter that 10000 iterations are sufficient in achieving convergence. The coefficient of variation (V) of each input variable was assumed to be constant when comparing alternative input probability distributions.

The final part of the analysis consists of a series of statistical evaluations of the generated results in terms of mean, standard deviation, skewness, kurtosis, maximum and minimum values. The probability of the hypothetical construction automation investment being non-profitable (i.e., $NPV < 0$) and resulting in a 'no-go' investment decision were also evaluated in this analysis.

5.6.1 Advantages and disadvantages

Probabilistic risk analysis has been successful in terms of its predictive ability and consequent assistance to managers in decision-making (Perry & Hayes 1985). Probabilistic risk analysis permits the investment decision analyst to evaluate many different combinations of investment conditions and operating scenarios at moderate cost. Risk

analysis provides decision-makers with insight into which factors are of importance and gives an indication of where effort should be concentrated in estimations. Interaction with a simulation model may provide managers with a more in-depth understanding of the pertinent investment issues.

The need to establish various statistical distributions based upon purely subjective thought and describing the correlations and dependencies of these interrelated input variables generate difficulties when applying MCS techniques. Any possible error that may be introduced within the input distribution assumptions are insignificant when compared with the error inherent in the subjective data which is by no means precise (Chau 1995). Hull (1980) concluded that the realism of an investment appraisal depends upon the accuracy of the estimates, which are made for the variables.

Disadvantages associated with MCS and the NPV risk profile approach highlighted by Hertz (1983) include:

- large fluctuations in cash flow distribution in a particular year may invalidate the assumption of a constant rate for investment and borrowing;
- changes in the cash flow pattern of a project may cause greater than proportionate changes in the NPV's;
- the choice of the cost of capital may affect the NPV and its standard deviation (higher discount rates reduce NPV standard deviation yet, intuitively, higher discount rates imply that the firm requires higher discount premiums), and
- difficulties associated with interpreting the NPV risk profiles.

Ho and Pike (1991) outline the major problems associated with risk analysis as a lack of sufficient data, difficulties in defining probabilities, correlation assumptions between input variables and the understanding of output information. Despite these disadvantages, probabilistic financial risk analysis provides a valuable decision support tool for investment appraisal. Furthermore, the use of probabilistic risk analysis provides construction professionals with the ability to thoroughly examine investment decisions prior to the allocation of large quantities of scarce capital resources. Risk analysis will assist in investigating the economic feasibility investment in automated construction technologies.

5.6.2 Palisade @RISK version 3.52

In the present research, all stochastic simulations were conducted using the @Risk (pronounced “at risk”) Release 3.52 computer package (Palisade Corporation 1998). @Risk is a commercially available software package primarily utilised for the analysis of risk in business and technical situations.

With @Risk, single point (discrete) cash flow estimates for investment appraisals (NPV analyses) may be replaced directly within traditional Microsoft Excel spreadsheets with probability distributions. The uncertainty present within estimates may be explicitly included within estimates to generate results that depict all possible future outcomes. @Risk facilitates the definition of uncertain cell values within Excel spreadsheets as probability function using functions. @Risk 3.52 adds thirty functions to the existing Excel function set, each of which allows the decision analyst to specify a different distribution type for cell values. Available distribution types include Beta, Exponential, Log-normal, Normal, Poisson, Triangular and Uniform.

Both Monte Carlo and Latin Hyper-cube simulation techniques are available and have been utilised throughout the present research. High-resolution graphics provide histograms, cumulative curves and tornado graphs. The simulations in the present research were performed using an IBM compatible Pentium MMX 166 MHz with 64 Mb of RAM. A simulation incorporating 17 input variables with 50000 iterations using a combination of @Risk 3.52 and Microsoft Excel 1997 takes approximately 6 minutes to converge.

5.7 Classification of input variables

The financial risk analysis methodology using Monte Carlo simulation was described in Section 5.6. The following sections describe the various input parameters that must be described and incorporated within a financial risk analysis of a construction automation investment opportunity. Prior to simulating the net present value risk profile of the proposed investment opportunity, the probability distribution function for each uncertain input parameter must be determined using either historical data or subjective judgement.

Cooper (1975) claims that the difficulties associated with estimation could be reduced if managers considered a range of possible outcomes, with each estimate being qualified by an expression of the probability of its occurrence.

From a purely financial risk perspective, total risk can be defined as a function of the associated ownership and operating costs of an automated construction system. These four sub-categories are highlighted in the taxonomy of construction automation investment risk. The following sub-sections describe the input variables incorporated within the developed risk analysis model.

5.7.1 Ownership costs

The ownership costs of an item of plant and machinery relate to those costs which despite actual use of the machine, must be incurred in order to purchase the system and its associated ancillaries. The following sub-sections describe these costs, examine their treatment in the existing literature and their incorporation within the present risk analysis model.

Purchase price

In accordance with the methodology adopted by Smith (1994), a probability distribution is not used to describe the initial purchase price of the machine under consideration. It is assumed that, unlike the uncertain future cash flows, the initial investment will take place now rather than in the future and there is therefore no uncertainty surrounding it. This is a simplifying assumption designed to assist the exposition. However, Woodward (1997) describes the division of initial capital costs into three sub-categories, namely:

- purchase costs;
- acquisition and finance costs, and
- installation, education and training costs.

It is assumed in the present study that the above costs are incorporated within the initial purchase price of the machine and that this price is incorporated as a discrete value. Manufacturers estimates of prototype machine purchase costs are used where available. However, the actual cost of adapted manufacturing manipulators is more widely available within the existing literature.

Cost of capital

The cost of capital is a significant input parameter for capital investment decision making. Blanket-rate discounted cash flow (DCF) appraisal techniques do not offer a measure of the precise reward investors should seek for undertaking a project within an unknown risk category. DCF techniques often succumb to the misapplication of excessive discount rates, which diminishes the benefits associated with future cash flows (Wilkes & Samuels 1991; Adler 2000).

Solitary discount rates, if applied uniformly throughout companies divisional sectors, may result in the acceptance of projects that should be rejected because they do not provide a commensurate return for the level of risk assumed. The application of a single hurdle rate assumes that there have been no adjustments to the financial risk exposure of the company since the rate was calculated. This technique may not be justified for major new investments, acquisitions or product developments in fields unrelated to the companies historical and existing operations. For a new high-risk venture, it may be wise to not rely on conventional intuitive risk adjusted discount rates for discounted cash flow analyses. Ho and Pike (1991) claim that setting discount rates arbitrarily without using formal risk measurement or using a refined method such as the CAPM may lead to setting discount rates too high and subsequently missing opportunities for profit and growth. The careful estimation of cash flows and the accurate calculation of discount rates will lead to more informed decision-making when making acquisitions and investments.

Farid *et al* (1989) concludes that the 'firm in market' context is the most appropriate for simple accept or reject investment decision making in the construction sector. They advocate the use of the WACC technique. This technique stipulates that the cost of the

individual sources of finance must be weighted by their corresponding proportions within the overall pool of financing. Figure 5.6 shows the alternative sources of financing projects for private and stock market quoted organisations.

The WACC has two components; the cost of debt and the cost of equity capital. The cost of equity is a measure of the minimum return that stockholders must receive to be properly compensated for their risk exposure. The cost of debt is market related and reflects the returns that lenders expect within the market place dependant upon the risk undertaken. Owing to the difficulties associated with obtaining corporate debt information, the yield to maturity on long dated treasury stock is assumed as an approximation for the cost of debt capital for quoted construction organisations. However, the cost of debt capital for non-quoted organisations will depend upon the cost of the debt instrument utilised, the risk perception of the lenders and the level of existing debt.

Calculation of the WACC uses accounting information and market-based data to derive a cost of capital.

$$WACC = \left[K_E \times \left(\frac{V_E}{V_E + V_D} \right) \right] + \left[K_{DAT} \times \left(\frac{V_D}{V_E + V_D} \right) \right] \quad 5.40$$

where K_{DAT} is the cost of debt capital after tax ($K_{DAT} = K_D \times (1 - T)$);

T is the rate of corporate taxation;

K_E is the cost of equity capital (from the CAPM);

V_E value of equity (market capitalisation), and

V_D is the value of debt.

The refined risk analysis approach incorporates probabilistic risk analysis and the CAPM in order to account for shareholders preferences (Ho & Pike 1991). The CAPM has been outlined as an appropriate method for determining market based risk-adjusted discount rates for investment appraisal purposes (Kulatilaka 1984; Farid *et al* 1989). The CAPM (Sharpe 1964; Linter 1965; Mossin 1966), is a mathematical technique for incorporating a price for risk within the calculation of the cost of capital. The model provides a relationship between a company's market risk and its required rate of return, i.e. the degree to which a companies risk premium varies with the average risk premium on the stock market. Recognising its limitations and unrealistic assumptions, the CAPM provides a rational framework for the evaluation of market based discount rate based upon the historical market returns on an industrial sector or an individual company's equity.

The CAPM provides a relationship between a company's systematic risk and its required rate of return. Widespread use of the CAPM is due to its strong theoretical foundation and its simplicity (Kaplan & Peterson 1998). The relationship between the variation of an equities risk premium and the stock market risk premium can be observed directly from the stock market. By plotting the return on a company's shares (R_S) against the return on the market index (R_M), a relationship between these two parameters can be assessed. Figure 5.7 represents a market model and depicts the characteristic line for a UK based quoted plant hire organisation.

The slope of the characteristic line indicates how the return on an equity is expected to vary for a given change in the stock market, i.e. how R_S and R_M are systematically related. The term used to describe this relationship is the beta coefficient (β). Beta measures the degree

to which a company's performance is affected by macro-economic forces, e.g. the rate of national economic growth, inflation levels, exchange rate movements and interest rates.

The rate of return expected by shareholders may be expressed as:

$$E(r) = R_f + (E(R_M) - R_f) \times \beta \quad 5.41$$

where $E(r)$ is the project cost of capital;

R_f is the risk-free rate of return;

$(E(R_M) - R_f)$ is the market risk premium; and

β is the systematic measure of market risk.

The beta coefficient may be expressed as:

$$\beta = \frac{\rho_{SM} \sigma_S}{\sigma_M} \quad 5.42$$

where ρ_{SM} is the coefficient of variation between the shares and the market;

σ_S is the standard deviation of the return on the shares; and

σ_M is the standard deviation of the return on the market.

Many of the assumptions used to construct the CAPM are unrealistic. However, the final test of such a model is its ability to forecast, not whether the presuppositions are correct (Adams *et al* 1993). There may be many factors which determine returns (e.g. company size and dividend policy), but it appears that relative systematic risk (β) is the most significant factor.

Table 5.2 presents market model data for the top ten UK construction and civil engineering contracting organisations. It is evident that specific risk is highly influential within the UK construction industry. The portfolio of construction contractors showed specific risk ranging from 34.8% of total risk to 95.3% of total risk. These values indicate that the variability of overall returns on these securities is influenced by factors specific to the construction industry and less so by market related factors. The mean and standard deviation of the calculated rates of return were 12.99% and 5.43% respectively. The contractors CAPM expected rates of return range from 3.22% to 23.63%.

In relation to the London Business School risk management service value of 1.29 (Samuels *et al* 1999) for the UK building and construction industry, the value of 0.82 indicates that the construction industry has become more defensive, which has reduced the industries systematic risk. In valuing advanced manufacturing technology, Wilkes and Samuels (1991) reports that discount rates applied are in the range of 5% to 30%. Pike and Neale (1999) suggest that a selection of subjective required rates of return may be applied to investment projects of different risk categories. Table 5.3 presents an outline of the investment project categories and their subjective required rates of return. Depending upon the subjective risk category of the investment, the required rate of return varies from 12% to 25%.

For simplicity, Smith (1994) assume that the project discount rate is known for certain and that it remains unchanged throughout the life of the project. However, it is important to update such calculations as new information arises. The investment methodology presented, assumes that the cost of capital will be subject to variation and the uncertainty

surrounding this input variable is accounted for by describing it as a probability distribution using the available market data.

Reimann (1990) states that the careful projection of future cash flow patterns will have a far greater impact on accurate valuation than trying to fine tune hurdle rates to be used in discounting these cash flows. Therefore, the following sections describe the means by which these cash flows have been estimated where required.

Functional life

Owing to the harsh and unstructured construction site environment, the economic working life of construction automation technologies is significantly reduced when compared to those of manufacturing systems. Bonini (1975) comments that the physical and economic life of an investment project is usually not known at the time the project is evaluated. Furthermore, uncertainty about economic life can have a large effect on the variability of the calculated NPV.

Kulatilaka (1984) provides a valuation framework for advanced manufacturing technology and with a worked example assumes that the economic life of the manufacturing manipulator is ten years. Warszawski (1985; 1986) assumes that the economic life of a construction robot would range between three and five years. He comments that the lower estimate reflects the accelerated wear under the rugged construction site conditions. In valuing a multi purpose interior finishing robot, Warszawski and Rosenfeld (1993; 1994) assume that the economic life of the adapted Funac S-700 manipulator would be between four and six years. Finally, Warszawski (1999) assumes that the average economic life of

an automated construction system would be 5 years due to the harsh and unstructured construction site environment.

Woodward (1997) comments upon the influence that the forecast life of an asset has upon its life cycle costs. He highlights the five possible determinants of an assets life expectancy:

- *Functional life* – the period over which the need for the asset is anticipated.
- *Physical life* – the period over which the asset is expected to last physically, to when major replacement or major rehabilitation is required.
- *Technological life* – the period until which technological obsolescence dictates replacement due to the development of a technologically superior alternative.
- *Economic life* – the period until which economic obsolescence dictates replacement with a lower cost alternative.
- *Social and legal life* – the period until which human desire or legal requirements dictate replacement.

When considering construction automation investment it is imperative to assess the assets value in relation to alternative values of functional life. In the present study, the machine functional or economic life is assumed to be five years.

Residual value

The residual value of a machine is the final disposal value of the machine, as scrap, at the end of its economic life. In estimating the life maintenance costs of traditional construction plant and machinery, Edwards *et al* (2000a) comments upon the possibility of this value

varying due to the method of disposal used. They highlight that trade-in prices from manufacturers against a new item generally attain the highest value, since manufacturers would cut their profits in order to attain machine sales. Specifically, Edwards (*ibid*) estimates that a machine's residual value equates to 10% of the machine original purchase price. However, Warszawski (1985) assumes that the salvage value of a construction robot would be negligible due to the harsh operating conditions. This may be an underestimation of the machine's ability to withstand the operating environment for which it has been designed. In the present study, a residual value of 10% of the initial purchase price is assumed.

5.7.2 Operating costs

Within existing literature, operating costs of construction mechatronics have been attributed to the end-users of such technology. Assuming that plant-hire organisations will be directly involved in the employment and use of such technology, it is imperative to attribute these costs to the owner of the machine or the party who directly incurs these costs. The operating costs are primarily dependent upon the total operating hours, which a machine undertakes per annum. Maintenance and repair costs are then directly related to the total operational hours. Operating costs specific to automated construction technology include consumable resources (e.g. oil, grease), inter-site and intra-site transfer costs, site set-up costs, the operators annual or hourly rate of pay and any insurance or license costs which are required over and above those already incurred with traditional plant and machinery. The following sub-sections describe these costs, examine their treatment in the existing literature and their incorporation within the present risk analysis model.

Rate of utilisation

Rosenfeld *et al* (1992) conducted full-scale experiments with TAMIR and compared the robots performance with traditional human labour techniques. As a base case, they assume that the robot would be utilised for 6 hours per day and for 250 days per year. This allows for approximately 2-3 hours for preparations, cleaning, trouble shooting and maintenance. When conducting a sensitivity analysis of their calculations, they assume that the machine may be utilised for 2000 or even 2500 hours per year. Najafi and Fu (1992) presented a feasibility study of the MIT Walbots. In their calculations they assume that the machine would be used for 800 hours per year. Despite this low rate of utilisation, the system was considerably more economical than traditional labour per unit cost. In more recent studies involving TAMIR, Warszawski and Rosenfeld (1993; 1994) assume that the system would utilised at a rate ranging from 1500 to 2000 hours per year.

The rate of machine utilisation may be subject to uncertainty because of the following factors (Taylor 1981):

1. low utilisation of equipment may be due to the equipment not being suited to the needs of contractors or because the machines service is not required;
2. poor performance, because the equipment does not produce the specified quality of output required, and
3. poor reliability because of mechanical design failures.

The relevance of factors 2 and 3 is questionable due to the extensive testing and evaluation that automated construction technologies will require prior to on-site use. However, the

demand of such technologies is of substantial significance to their value to a plant-hire organisation.

Edwards *et al* (2000b) assumed that construction excavators would be used for 3000 operational hours per annum, which assume 12 hours per day and 50 working weeks per year. However, this may be subject to variation. The uncertainty surrounding the daily and annual rate of utilisation will be examined through the proposed probabilistic risk analysis methodology.

Maintenance and repair costs

Repairs and maintenance may take longer to perform when compared to those of traditional construction plant and machinery. Machine down-times, i.e. the cost of lost production/hire revenue, may depend upon the nature of the system, its intensity of use, the operating environment and the service arrangements (Kulatilaka 1984).

Warszawski and Rosenfeld (1994) estimate the cost of repairs and high-level maintenance as a percentage of the initial purchase price of the machine. It was estimated as 10% of the initial purchase price and incorporated routine low-level maintenance. Machine maintenance costs tend to be comparatively low in the early on in a machine's life. Edwards *et al* (2000b) highlights that early faults and maintenance are confined to 'burn in' of components, where such costs are often covered under the manufacturer's warranty and are not borne by the machine owner.

The following components contribute towards the total repair and maintenance costs for automated construction technologies:

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- scheduled repair and maintenance costs, which are subject to growth with age and hours utilised;
- routine maintenance, which is performed on a daily basis by the machine operator or technician, and
- the machine down-time during scheduled repairs and maintenance.

The sensitivity of the total maintenance costs to downtime will be investigated in a following section of this chapter. Furthermore, the uncertainty surrounding this cost component will be investigated within the risk analysis framework.

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Consumable resources

These consumables include oil, grease and other components, which may be subject to wear due to the harsh operating environment within which automated construction systems will operate.

Inter-site and intra-site transfer costs

Similar to traditional plant and machinery, automated construction technologies must be transported to and from construction projects by road. Many items of construction plant are capable of inter-site transport under their on-board motive power and locomotive system. However, certain machine must be moved using an appropriate low-loader vehicle or vehicle with on-board loading crane. The cost of inter-site transportation depends upon the nature of the machine and its mobility. Existing automated construction technologies generally require transportation vehicles for inter-site transportation. Warzsawski and Rosenfeld (1994) assumed that the cost of an appropriate transportation vehicle should not

considered, since this cost is incurred in the transfer of traditional equipment. Within the present study, it is assumed that a plant-hire organisation will own a vehicle suitable for the transportation of traditional construction plant and that the cost of this vehicle will already be accounted for within the overheads of the organisation. Furthermore, many systems may require movement between work-stations within the confines of the construction project within which they are operating. Depending upon the complexity of the system and the required preparation time, these intra-site transportation costs may contribute to the overall operating costs of the system being valued. Inter-site transfer costs are estimated subjectively within this study. Variation of these costs and their effect upon the investment NPV risk profile are investigated.

These costs are dependant upon the total number of inter-site transfers required per annum. This cost is also dependant upon the total time utilised on each project. This may vary between different machines designed to conduct varying activities. Certain machines may be required for the complete duration of a project, whilst some may only be required for a short period of time. Also, the size of a project and the subsequent number of work stations will determine the total cost of intra-site transfers. This is also related to the set-up costs of the machine, which is described in the following section.

Site set-up costs

Depending upon the nature of the machine and the location of its operation, the cost of using an automated system may be dependent upon the costs associated with the installation of the machine and the preparation of the working environment.

Provision for the organisation of materials to suit automated application may include the pre-packing, palatisation and positioning of components to suit the specific automated system being utilised. Adjustments to site environment to suit automated operation of machine may include the surveying of the operating location and pre-programming using a teach-box to facilitate automated material conveyance and work execution. There may be, depending upon the navigation system utilised, requirements for the installation of markers either embedded in the floor surface (AGV's) or attached to existing columns or beams to assist in proximity determination. These are dependant upon the systems mode of operation and the use of on-board range sensors. If a tele-operated control system is utilised, there may be a reduction in the overall set-up costs. Furthermore, there may be a requirement to install working envelope protection barriers to prevent site operatives accidentally moving within the machine's zone of influence.

Operators pay

The rates of pay for plant hire operators vary considerably between hire companies and are dependant upon many factors. These rates may be dependant upon the tenure of the hire period – longer hire periods may give rise to lower charges. The cost of plant operators, based upon average plus rates under the working rule agreement have been classified into four categories and published within the CESMM 3 1999/2000 price database (EC Harris 1999). The following categories of plant operator hourly pay have been adopted for this research:

- *Class 1* £9.58 per hour
- *Class 2* £8.65 per hour

It is assumed that these costs will not be subject to uncertainty and, within the risk analysis framework, are described as discrete costs. However, there is the possibility that the rate of pay for a machine operator with greater technical knowledge and operating expertise may be above those for operating traditional plant and machinery. The effect of variation in the operator's rate of pay upon operating costs will be examined. Specifically, a range of potential hourly pay rates in the form of a probability distribution will be used to assess the overall effect of such costs.

Insurance and operating licenses

The cost of insuring automated construction systems is, at present, assumed to be of similar cost to traditional construction plant and machinery. However, as such technologies become more widespread and more technologically sophisticated, the cost incurred may increase. Owing to the unique nature of construction automation, in order to operate such systems there may be legal requirements (as in the manufacturing industry) for appropriate operating licenses. Construction contractors buy insurance that is based on their previous performance, savings due to reduced accidents will not benefit them in the short-term, but rather their insurance companies (Bernold 1998). However, the long-term benefits associated with decreased accidents may relate to improved corporate image.

5.7.3 Correlation and input variable dependence

In general, the larger the number of input variables within the risk analysis model, the greater the chance that correlation or dependence exists between the input parameters (Chau.1995). Touran and Wiser (1992) conclude that ignoring correlation between the input variables results in a serious error in the assessment of the standard deviation of the output criterion. This is a pertinent issue due to the use of the standard deviation as a measure of investment risk. Since the spread of the output distribution is a representation

of risk, excluding correlations might result in the erroneous assessment of the risk of the project (Wall 1997; Touran 1993).

Positive correlation exists when the value of one variable increases as the value of another correlated variable increases. In this case, the value of the correlation coefficient will be greater than 0. Perfect correlation exists when the entire variation in one variable is due to the increase or decrease in another variable. In this case, the correlation coefficient will be equal to 1. However, it is often the case that as one variable increases another correlated variable will decrease. This is known as negative correlation and is described using a correlation coefficient of less than 0. In using the correlation coefficient, the investment analyst must be sure that the association between the two variables is likely, or at least possible (Owen & Jones 1994).

If the correlation between two input parameters is relatively small, the assumption of independence will not generate large errors (Touran & Wiser 1992). By sampling the various input p.d.f.'s independently, it is assumed that any correlation between the input variables is neglected (Touran & Wiser 1992). In addition to specifying subjective input probability distributions and their relevant parameters, the analyst must specify subjective coefficients of correlation between any correlated input variables. It may be reasonable to expect an estimator to provide a qualitative value for the correlation coefficient. Touran (1993) suggests that an expert may be able to estimate a correlation as weak, moderate or strong. For example, an investment analyst may not be able to state the exact value for the correlation coefficient between the annual hours utilised and the total consumables (e.g. lubricants etc) required, however, he may know that these costs are strongly correlated. Historical data is required to test whether dependence exists between the model input

parameters (Chau 1995). However, this type of historical data is not yet available for automated construction systems.

5.8 Inflation

Inflation is the increase in the general level of prices. Inflation determines the real value or purchasing power of savings. It affects increases in pensions and other state benefits and plays an important role in wage bargaining.

Rising costs are passed onto customers as firms raise their prices to maintain their profit margins. If wage costs are stimulating price rises (most of total net costs of the economy), firms can only raise their prices if there is demand for their goods – if not, high costs merely bankrupt them. When aggregate demand (consumer goods and services) is greater than the total of goods and services that firms can supply, there is excess demand in the economy. Excess demand causes producers to raise their prices – but this leads workers to demand higher wages to maintain their living standards; this causes higher demand and the process begins again.

These all amount to an attempt by a nation to live beyond its means, or to enjoy a living standard higher than that allowed by its output and borrowing. Inflation can not be cured by a measure, which does not suppress attempts at maintaining high living standards – reduction in inflation is associated with severe measures.

The most widely quoted index of inflation is the ‘retail price index’ (RPI), which is an index of the average change in the prices of consumer products represented by a ‘basket’ of goods. Changes in the retail price index from year to year give a percentage value for the rate of inflation. If the value of inflation is 5%, this signifies that the RPI has risen by 5%

since the same month of the previous year; the cost of the basket of goods increasing by 5%. Due to inflation, the inputs and outputs from the plant investment may rise over time, and the magnitude of these changes may have to be estimated. To adjust for inflation, the investment analyst is required to make an estimation of the future rate of inflation.

The treatment of inflation affects future cash flows and the cost of capital used to discount the cash flows to present value terms. Inflation influences monetary returns and the criterion for establishing the acceptability of those returns. An assumption must be made concerning the rate of inflation that is incorporated in the investment appraisal. Alternatively, inflation can be incorporated within cash flow estimations by applying the general rate of inflation to calculate all project cash flows in real terms.

The correct treatment of inflation requires a comparison of like with like (Coulthrust 1986; Drury & Tayles 1997). Real costs of capital must be applied to real cash flows or nominal costs of capital to nominal cash flows. As market data is utilised to derive the cost of capital for the selected organisations, the value must only be used to discount nominal cash flows.

The two definitions of cash flow are:

- nominal project cash flows discounted by a nominal (market) discount rate to present value cash flows; or
- real project cash flows discounted by a real discount rate, assuming a general rate of inflation.

The Fisher (1965) equation can be utilised to deflate nominal cash flows and discount rates into real or consumption values by assuming a constant general rate of inflation. The general rate of inflation may be assumed to be the retail price index (RPI).

The Fisher relationship is:

$$\frac{(1+n)}{(1+i)} = (1+r) \quad 5.46$$

where r is the real (purchasing power or money) interest rate;

i is the general rate of inflation, and

n is the nominal (market) interest rate (quoted by banks and lenders).

In this study, it is assumed that all estimated cash flows are nominal and that the cost of capital is nominal. Subsequently, no calculations to remove inflation in the investment appraisal methodology are incorporated.

5.9 Taxation

Taxation can create significant effects upon investment decisions. Taxation is significant in investment appraisal as it can have a notable influence on the desirability of the appraisal outcome (Samuels *et al* 1999; Pike & Neale 1999; Lumby 1994; Flanagan & Norman 1993; Dixon 1988). The literature review led the author to believe that although the effects of taxation are minimal; they must be incorporated to present a more realistic description of the returns expected from the proposed investment.

Corporate taxation is not calculated on a project basis, but the tax bill will increase with every new profitable project and reduce as a result of a project incurring losses. Corporate taxation is included to ensure that, after taxation and capital allowances, investment in the appraised systems will remain feasible. The NPV calculations have incorporated allowances for corporate taxation, so as to account for the effects of taxation upon the investment profitability decision criterion. Table 5.4 shows the calculation of the annual net discounted cash flows.

5.10 Capital Allowances

In the UK tax relief is available on capital expenditure in the form of an initial first year allowance and 25% in subsequent years on a declining balance basis (Rowes 1999, Pike & Neale 1999). Discrepancy between the written-down value (WDV) and the disposal value may cause a tax liability or generate a tax relief. Capital allowances have been accounted for using the methodology outlined by Pike and Neale (1999). Table 5.5 shows the method of calculating the capital allowances. The initial WDA was calculated as 25% of the initial outlay. The second WDA is calculated as 25% of the initial outlay minus 25%. The third, fourth and fifth are calculated in a similar manner. Within the appraisal methodologies adopted, the residual value of the machine has been assumed to be 10% of the initial purchase cost, therefore, a balancing allowance of £21,640.63 is generated. Tax relief was calculated as 30% of the WDA for each year. Net-cash flows were calculated as follows:

$$\text{Net cash flow} = (\text{Pre-tax cash flow} - \text{corporate tax}) + \text{tax relief on WDA} \quad 5.47$$

The resultant net cash flows are then discounted using the estimated project cost of capital. Subsequently, the investment profitability criterion is net of taxation.

5.11 Numerical example: base parameters

The numerical example presented within this chapter is concerned with the purchase and subsequent hire of a tele-operated system. The developed appraisal model example incorporates a series of general assumptions, which must be considered prior to the valuation of prototype technologies. These assumptions are based upon data accumulated from the limited existing literature regarding the economic valuation of automated construction technology. Table 5.6 summarises these numerical assumptions. These assumptions are as follows:

- *Initial purchase price, P* : assumed to be £100,000.00.
- *Annual hours utilised, H_{yr}* : assumed to be 2500 per annum.
- *Working day, H_{day}* : assumed to be 8 hours per day.
- *Functional life, n* : assumed to be 5 years due to the harsh operating environment.
- *Depreciation, D_i* : declining balance method as a percentage of the initial purchase cost.
- *Number of inter-site transfers per annum, n_i* : 7 inter-site transfers per annum, which included 2 for scheduled maintenance undertaken at hire depot or manufacturers facilities.
- *Number of work stations per site, n_{sm}* : average number of work stations per site is assumed to be 10.
- *Work stations transfer time, H_{sm}* : assumed to be approximately 30 minutes for each stations transfer.
- *Site set-up costs, S_s* : these are estimated to be approximately £1000.00 per site.

- *Rate of interest or discount rate, i* : base case assumed to be 10%. However, this fixed value may be subject to variation and is not assumed to be constant throughout the analysis.
- *Consumable resources, F* : assumed to be £250.00 per annum. However, this value is dependent upon the rate of utilisation and the complexity of any moving part (e.g. hydraulic systems for lifting large loads compared to similar systems for paint application)
- *Annual cost of insurance premium, I* : special insurance may be required for automated construction systems. Base value assumed to be £500.00 per annum.
- *Annual cost of operating licenses, l* : special-operating licenses may be required further to inspection from industrial automated systems inspectorate. Base case assumed to be £250.00 per annum.
- *Scheduled maintenance cost as a % of P , ϕ* : is assumed that the scheduled maintenance will be approximate to a percentage of the initial purchase price per annum. The percentage value assumed would be dependent upon the nature of the system and it's operating environment. A value of 10% is assumed.
- *Annual scheduled maintenance*: grows exponentially as a function of the functional life of the machine and a percentage of the initial purchase price. Base case growth factor (θ) assumed to be 0.15.
- *Routine maintenance time period, M_i* : assumed to be 30 minutes per working day. This includes any daily application of lubricants or diagnostic testing of operating systems.
- *Operators hourly rate of pay, L_{op}* : assumed to be CESSM 3 Price Database Class 1 plant operator hourly pay rate of £9.58.

Utilising the above numerical assumptions, the following sections present the results of the probabilistic financial risk analysis model. Initially, overall results are presented, followed by investigation of the sensitivity of the profitability measure to variations in each of the input variables.

5.12 Results; plant-hire valuation model

This section presents the results from the Monte Carlo probabilistic financial risk analysis using the authors plant hire valuation model. A total of 17 input variables were used to describe the cost components of the hypothetical investment opportunity. The 17 input variables and their base case value estimations were described in Section 5.7.

A summary of the statistical properties of the predicted NPV risk profile is presented. The effect of varying the number of iterations per simulation, input variable correlation, varying input probability distribution types, mean values for each input variable are presented in the following sub-sections.

Unless otherwise stated in the text, the number of iterations, input distribution type, mean base case values and correlation coefficients used in all analyses were 50000, normal, medium correlation and mean values as outlined in Table 5.6.

5.12.1 The effect of varying the cost of inter-site transfers

Figure 5.8 shows the effect of varying the mean cost of each inter-site transfer upon the predicted NPV risk profile. The mean values assumed were £550.00, £600.00, £650.00 and £700.00 per inter-site transfer. Table 5.7 shows statistical data for each simulated NPV risk profile. By increasing the mean cost of each inter-site transfer from £500.00 to £700.00,

the simulated investment NPV mean increased from -£4557.36 to -£939.64. Similarly, the standard deviation of the investment returns increased from £10783.23 to £11162.17. The same increase in mean cost of inter-site transfers decreased the probability of investment being non-profitable (i.e. $NPV \leq 0$) from 68.09% to 55.34%.

5.12.2 The effect of varying the cost of operating licenses

Figure 5.9 shows the effect of varying the mean annual cost of the operating licenses upon the simulated NPV risk profile. The mean values assumed were £300.00, £350.00, £400.00 and £450.00 per annum. Table 5.8 shows the statistical data for each simulated NPV risk profile. By increasing the mean value of the machines operating licenses from £250.00 to £450.00, the simulated investment NPV mean increased from -£4557.36 to -£4498.88. Similarly, the standard deviation of the investment returns increased from £10783.23 to £10852.88. The same increase in the mean cost of operating licenses decreased the probability of the investment being non-profitable (i.e., $NPV \leq 0$) from 68.09% to 67.53%.

5.12.3 The effect of varying the cost of annual insurance premiums

Figure 5.10 shows the effect of varying the mean annual cost of the associated insurance premiums upon the predicted NPV risk profile. The mean values assumed were £550.00, £600.00, £650.00 and £700.00 per annum. Table 5.9 shows the statistical data for each simulated NPV risk profile. By increasing the mean value of the annual cost of the machines insurance premiums from £500.00 to £700.00, the simulated investment NPV mean increased from -£4557.36 to -£4504.52. Similarly, the standard deviation of investment returns increased from £10783.23 to £10851.78. A similar increase in the annual cost of the insurance premium reduced the probability of the investment being non-profitable (i.e., $NPV \leq 0$) from 68.09% to 67.74%.

5.12.4 The effect of varying the total hours utilised per annum

Figure 5.11 shows the effect of varying the mean total hours utilised per annum upon the prediction of the NPV risk profile. The values used in this study were based upon those outlined within the existing literature. Table 5.10 shows the statistical data for each simulated NPV risk profile. The mean values used were 2000, 2250, and 2500. Increasing the total hours utilised from 2000 to 2500 hours per annum caused the predicted mean NPV to increase from -£4557.36 to -£3149.29. The standard deviation of the NPV increased from £10783.23 to £10913.54. Furthermore, the probability of the investment being non-profitable (i.e., $NPV \leq 0$) was reduced from 68.09% to 63.12%.

5.12.5 The effect of varying operators hourly rate of pay

Figure 5.12 shows the effect of varying the machine operators hourly rate of pay upon the generated NPV financial risk profile. Two existing hourly rates of pay for traditional construction plant were adopted for this study. These were obtained from the CESSM 3 Price Database (EC Harris 1999). Table 5.11 shows the statistical data for the simulated NPV risk profiles. The *Class 2* (£8.65) rate of pay generated a mean NPV of -£4874.31 with the investment returns having a standard deviation of £10806.04. The *Class 1* (£9.58) rate of pay generated a mean NPV of -£4302.52 with the investment returns having a standard deviation of £10864.90. Increasing the mean operator's rate of pay from £8.65 to £15.00 caused the NPV mean to increase from -£4874.31 to -£874.69. Similarly, for the same increase in the hourly rate of pay, the standard deviation of the investment returns increased from £10806.04 to £11148.83. Furthermore, the probability of the investment being non-profitable (i.e., $NPV \leq 0$) was reduced from 68.94% to 55.11%.

5.12.6 The effect of varying the average hours utilised per day

Figure 5.13 shows the effect of varying the mean hours utilised per average working day upon the NPV risk profile. The mean values adopted within this study were 6, 7, 8, 9 and 10. It can be seen that from Figure 5.13 that the daily hours utilised had an insignificant influence upon the predicted NPV risk profile especially for the higher mean values. Table 5.12 shows the statistical data for the simulated NPV risk profiles. Increasing the mean hours utilised per average working day from 6 to 10 hours caused the simulated mean NPV to decrease from -£4524.40 to -£4667.61. The standard deviation of the simulated NPV decreased from £10866.01 to £10829.20. Furthermore, the probability of the investment being non-profitable was increased from 67.68% to 68.33%.

5.12.7 The effect of varying the daily routine maintenance period

Figure 5.14 shows the effect of varying the mean daily routine maintenance period upon the NPV risk profile. Table 5.13 shows the statistical data for the simulated NPV risk profiles. By increasing the daily maintenance period from 30 minutes to 60 minutes, the mean NPV increased from -£4557.36 to -£4248.32. With a similar increase, the standard deviation of the returns increased from £10783.23 to £10827.12. Furthermore, the probability of the investment being non-profitable was decreased from 68.09% to 66.75%.

5.12.8 The effect of varying the number of work stations per project

Figure 5.15 shows the effect of varying the number of operating work stations per project upon the NPV risk profile. The mean number of work station's per project were 12, 14, 16, 18 and 20. Table 5.14 shows the statistical data for the simulated NPV risk profiles. By varying the number of workstations in the analysis, the effect upon the NPV based upon the layout and size of the project may be examined. The overall effect of varying the number

of work station's per project was minimal. By increasing the number of work stations from 12 to 20, the mean NPV decreased from -£4464.54 to -£4480.67. With a similar increase, the standard deviation of returns decreased from £10658.03 to £10587.32. Furthermore, the probability of the investment being non-profitable increased from 67.65% to 67.75%. This increase is evidence that the effect of varying the number of work-station's per project does not significantly influence the profitability of the investment.

5.12.9 The effect of varying the work station transfer period

Figure 5.16 shows the effect of varying the work station transfer period upon the NPV risk profile. The mean work station transfer periods selected were 40, 50 and 60 minutes per station transfer. Table 5.15 shows the statistical data for the simulated NPV risk profiles. By increasing the work station transfer period from 40 minutes to 60 minutes, the mean NPV increased from -£4648.57 to -£4610.33. However, the standard deviation of returns decreased from £10681.09 to £10622.69. The probability of the investment being non-profitable decreased from 68.54% to 68.42%. These results indicate that the work station transfer period will have a negligible effect upon the value of the investment.

5.12.10 The effect of varying the cost of capital

Figure 5.17 shows the effect of varying the cost of capital or rate of interest upon the NPV risk profile. The mean values adopted in this study were 12.5%, 15%, 20% and 25%. Table 5.16 shows the statistical data for the simulated NPV risk profiles. The mean cost of capital assumed within the analysis had a significant effect upon the profitability of the hypothetical investment opportunity. By increasing the mean cost of capital from 12.5% to 25%, the mean NPV decreased from -£9199.25 to -£31718.72. However, the standard deviation of investment returns decreased from £9688.61 to £6424.85. Subsequently, the

probability of the investment being non-profitable increased from 83.51% to 99.99%. These results indicate that cost of capital may have a significant effect upon the profitability of construction automation investments.

5.12.11 The effect of varying the residual machine value

Figure 5.18 shows the effect of varying the residual or scrap value of the machine as a percentage of the initial purchase price, P . The mean values were calculated as a percentage of the initial purchase price of the machine. The percentage values adopted were 11% (£11000.00), 12% (£12000.00), 13% (£13000.00), 14% (£14000.00) and 15% (£15000.00). Table 5.17 shows the statistical data for the simulated NPV risk profiles. By increasing the residual value of the machine as a percentage of the initial purchase price, the mean NPV decreased from -£7334.04 to -£15936.67. Similarly, the standard deviation of the investment returns decreased from £10267.80 to £9211.00. Subsequently, the probability of the investment being non-profitable increased from 77.33% to 95.42%. These results indicate the investment is sensitive to increases in the residual value of the machine. The increased residual value decreases the annual ownership costs, which in turn, decreases the annual hire revenue. Subsequently, the reduction in hire revenue generates a reduction in the profitability of the investment.

5.12.12 The effect of varying the scheduled maintenance costs

Figure 5.19 shows the effect of varying the cost of scheduled machine maintenance, as a percentage value of the initial purchase price of the machine, upon the generated NPV risk profile. The mean percentage values adopted were 12.5% (0.125), 15% (0.15), 17.5% (0.175) and 20% (0.20). Table 5.18 shows the statistical data for the simulated NPV risk profiles. By increasing the mean scheduled maintenance costs, as a percentage of the

original purchase price of the machine, from 12.5% to 20%, the mean NPV decreased from -£2592.36 to -£8568.82. With a similar increase in the scheduled maintenance costs, the standard deviation of the investment returns increased from £10465.25 to £11258.16. The increase in maintenance costs had a significant effect upon the profitability of the investment. The probability of the investment being non-profitable was increased from 61.6% to 78.62%. These results indicate that the value of the investment is particularly sensitive to the scheduled maintenance costs.

5.12.13 The effect of varying the exponential growth rate of scheduled maintenance costs

Figure 5.20 shows the effect of varying the mean exponential growth rate factor upon the NPV risk profile prediction. The mean exponential growth rates adopted in this study were 0.10 (10%), 0.15 (15%), 0.20 (20%) and 0.25 (25%). Table 5.19 shows the statistical data for the simulated NPV risk profiles. By increasing the mean scheduled maintenance growth factor from 0.10 to 0.25, the predicted mean NPV decreased from £3673.62 to -£22488.07. A similar increase in the growth rate caused the standard deviation of the investment returns to increase from £10165.48 to £11770.30. The increase in the exponential rate of scheduled maintenance costs had a significant effect upon the profitability of the investment. The probability of the investment being non-profitable increased from 37.89% to 83.84%. These results indicate that the profitability of the investment is particularly sensitive to the rate at which the annual scheduled maintenance costs will increase with age and the cumulative machine running hours.

5.12.14 The effect of varying the input variable probability distribution types

Figure 5.21 shows a graphical comparison of the use of four different input probability distributions at 50000 iterations for the hypothetical investment opportunity. It can be seen that between 0.5 and 0.95 probabilities, the percentile values of the Normal, Triangular and Discrete distributions share similar values. The percentile values for the Uniform distribution are the most optimistic and, in comparison with the other distribution types, over estimate the up-side potential of the investment NPV risk profile.

Table 5.20 shows the statistical results for the comparison of the four input distribution types. It may be observed that after 50000 iterations, the results of the Normal, Triangular and Discrete input distribution types show little difference in their mean values. The mean values for the Normal, Triangular and Discrete distribution types with 50000 iterations are -£4557.36, -£4569.25 and -£4520.62, respectively. Furthermore, the standard deviation of returns for the Normal, Triangular and Discrete input distribution types are £10783.23, £10767.77 and £10770.46, respectively. However, the investment NPV risk profile range varies considerably between the minimum and maximum values. The simulated range for the Normal input distribution's produces a minimum value of -£50936.87 and a maximum value of £55107.07. The simulated range for the Triangular input distribution's produces a minimum value of -£43305.81 and a maximum value of £38307.69. The simulated range for the Discrete input distribution's produces a minimum value of -£37770.04 and a maximum value of £33292.90. From these results, it may be seen that the assumption of input parameters being normally distributed produces a greater range of possible NPV's and also generates the greatest standard deviation of returns. Finally, the Uniform distribution input produces the greatest value of mean and standard deviation of investment returns, £2353.36 and £11671.42 respectively. The simulated range for the input of a

Uniform distribution type produces a minimum value of -£35618.48 and a maximum value of £45816.26.

The range generated from the use of Normal input distribution types is due to the distribution being unbounded both to the left and right of the mean value. Therefore, a greater number of simulations generates a greater probability of the extreme values of each input distribution being selected in the random number generation process. This can also be seen in skewness and kurtosis of the normal NPV risk profile. The Uniform distribution allows extreme values for each input parameter to be included in the simulation with the same probability as all other values. Therefore, the results generated from the use of the Uniform distribution are overly optimistic and the general form of the distribution overestimates the probability of the extreme values in each input distribution occurring.

Therefore, it can be said that the results of the Normal, Triangular and Discrete input distribution types produce similar NPV risk profile output results. However, the Uniform input distribution type tends to produce an over optimistic investment NPV risk profile.

5.12.15 The effect of varying the number of iterations

Figure 5.22 to 5.27 show the effect of varying the number of iterations on the prediction of the NPV risk profile for the hypothetical automation investment opportunity. The number of iterations used in this study were 100, 1000, 5000, 10000, 25000 and 50000. Referring to Figure 5.22 to 5.27, it is evident that the number of iterations becomes significant for 5000 or more iterations. It is clear that from these figures that the greater the number of iterations produces an output distribution with a more regular shape. These results show

that by increasing the number of iterations, a reduction in the sampling variability is attained.

Figure 5.28 to 5.31 show a comparison of the different number of iterations per simulation for all four of the distribution forms. Table 5.21 to 5.24 show the equivalent statistical parameters resulting from using different iterations in each of the distribution forms used. From Table 5.21, increasing the number of iterations from 1000 to 50000 caused the predicted mean NPV to fall from -£4586.54 to -£4557.36. Similarly, the standard deviation of the predicted NPV fell from £10505.42 to £10783.23. The probability of the investment proposal being rejected increased from 72.70% to 68.09%.

The results show that for the hypothetical investment scenario, 5000 iterations, or more, within each simulation will provide sufficiently accurate results. For further confidence in the results it is recommended that 50000 iterations are used per simulation.

5.12.16 Sensitivity analysis

To illustrate the sensitivity of the NPV risk profile to the input variables. Multiple regression analysis was used to examine the effect of the multiple influences upon the investment NPV. The dependent variable (NPV) is related to n independent variable, X_1, X_2, \dots, X_n . If the independent variables take the specific values $x_{1i}, x_{2i}, \dots, x_{ni}$, then the multiple regression expresses the corresponding value of the dependent variable, NPV_i , as:

$$NPV_i = \alpha + \beta_1 x_{1i} + \beta_2 x_{2i} + \dots + \beta_n x_{ni} + \varepsilon_i \quad 5.48$$

where α , β_1 , β_2 , ..., β_n are constants and ϵ_i is a random variable with mean 0. The error term acknowledges that in the real world, no postulated relationship will hold precisely (Newbold 1991). This error term may be regarded as the amalgamation of the influences of the multitude of factors (other than those stipulated within the appraisal model) that may affect the profitability of a construction automation investment. The partial regression coefficients, β_i , measure the expected changes in the dependent variable resulting from a unit increase in one of the independent variables, *ceteris paribus*. The partial regression coefficients describe the separate impacts of the independent variables upon the dependent variables. However, they do not provide a direct measure of the strength of these relationships, since their numerical values depend upon the units in which the variables are measured (Newbold 1991).

Tables 5.25 and 5.26 show the partial regression coefficients and rank correlation coefficients for the NPV risk analysis model. Table 5.26 shows the multiple regression analysis results, assuming strong subjective input variable correlation. Table 5.27 shows results assuming that no subjective correlation exists between the input variables. The multiple regression analysis generated an R^2 value of 0.9717 when strong subjective correlation was assumed between the input variables. Similarly, an R^2 value of 0.9710 was calculated when no input variable correlation was assumed. These values indicate that linear regression does sufficiently explain the relationship between the input variables and the output profitability criterion. The findings indicate four fairly strong relationships, with a negative linear association between the cost of capital (interest rate), the site set-up costs, the exponential maintenance cost growth factor and the scheduled maintenance costs as a percentage of the initial purchase price.

5.13 Testing profitability output measure normality

This section examines the shape of the investment NPV output distribution (risk profile) from the Monte Carlo simulations. The predicted distribution of the investment NPV presented in Section 5.12 were used in this study. The Bowman-Shelton test for normality is based on the closeness to 0 of the sample skewness and the closeness to 3 of the sample kurtosis. The test statistics are:

$$Skewness = \frac{\sum_{i=1}^n (x_i - \bar{x})^3 / n}{\sigma^3} \quad 5.49$$

$$Kurtosis = \frac{\sum_{i=1}^n (x_i - \bar{x})^4 / n}{\sigma^4} \quad 5.50$$

$$B = n \left[\frac{(Skewness)^2}{6} + \frac{(Kurtosis-3)^2}{24} \right] \quad 5.51$$

where, n is the number of observations from the population.

Tables 5.27 presents the Bowman-Shelton test statistics for the simulated NPV risk profiles using the four input probability distribution types selected for this study. To test the null hypothesis that the true distribution for the NPV risk profile is normal, we find the statistic calculated in 5.28. Comparison of the results obtained with the significance points presented in Table 5.29 provides little ground for questioning the hypothesis that the NPV risk profile distribution is normal. However, it is essential that objective data is obtained, so as to test the suitability of the selected distribution functions in modelling construction mechatronics cash flows.

If there is a sufficiently large number of input variables, the central limit theorem (CLT) implies that the sum of the variables should approximate the variance (standard deviation) of the sub-system variables (Chau 1995). If a sample is relatively large, the sample means will turn out to be normally distributed. In fact, the greater the sample size, the closer the distribution of sample means will revert to a normal distribution. The central limit theorem implies that when a range of input distribution shapes is entered and simulated many times, there will, as the number of simulations increases, be a tendency for the output distribution to tend to a normal shape (Raftery 1994). Specifically, if the variables are independent, identically distributed random variables with finite means and variance, then their sum is approximately normal. Therefore, if the sequence of discounted cash flows can be assumed to be independent and have the same form of distribution, the distribution of NPV is approximately normal (Hertz 1983). However, Hertz concludes that the assumption of independence is restrictive and that it would be unlikely that the cash flow variables would be identically distributed in real life.

According to Hull (1980) and Hertz (1983), the NPV risk profile is likely to be normal in investment situations except when:

- the investor has options (e.g., abandonment or expansion options) open at stages throughout the machines functional life;
- the distribution of the NPV risk profile is heavily influenced by non-linearities in the cash flow estimation model; and
- there are a small number of uncertain variables, or the uncertainty in one variable dominates all other uncertainties

Within the present study, the investor has a series of strategic options, which include the option to abandon the machine deployment and sell it on the second hand market and the option to purchase more machines and expand the firms operations with this specific technology. Furthermore, from the previous section (Section 5.12) is evident that four of the input variables dominate the other input variables with regards to their uncertainty and its effect upon the NPV risk profile. However, historical and objective machine implementation data is required to provide accurate descriptions of the input variable probability distributions prior to the accurate assessment of the NPV risk profile probability distribution type.

5.14 Discussion of results

This section discusses the results obtained in the use of Monte Carlo simulation for the analysis of financial risk in the presented hypothetical automated construction systems investment. The influence of each input parameter upon investment risk is also discussed. Following this, the limitations of the technique are discussed.

5.14.1 Discussion; analysis of construction automation investment risk

This chapter has presented a framework for defining the financial cash flow and costs associated with investment in construction mechatronics technologies in the presence of uncertainty. Typical sources of uncertainty were identified and a financial risk analysis model was constructed to evaluate an NPV risk profile using Monte Carlo simulation. Risk was quantified as the standard deviation of investment returns and the probability of the NPV being less than zero.

5.14.2 Limitations of approach

The NPV investment appraisal technique has been widely used for the analysis of construction industry related investment analyses. Specifically, the NPV technique has been adopted in the appraisal of construction automation investment opportunities. However, the use of the NPV technique alone and in particular the use of discrete estimates for associated costs and expenditures does not incorporate the uncertainty surrounding these values. Due to the developmental stage of construction automation technology and a distinct lack of historical implementation data, many subjective estimates must be made when conducting investment appraisals. This particular problem is the prime reasoning for the application of financial risk analysis to the appraisal of construction automation investment opportunities.

The determination of mean values for the risk analysis input variables may be based upon the existing academic studies relating to the economic comparison of manual and automated construction activities. However, there a selection of variables, which must be estimated subjectively due to a significant lack of historical implementation data. The estimates for the range and standard deviations for each input variable can only be assumed subjectively, due to the lack of appropriate objective data concerning the implementation of construction mechatronics technology. The validity of an investment appraisal depends upon the accuracy and reliability of the estimates used to determine the likely values for the input variables.

At present, it is highly unlikely that those contractors (especially the Japanese) who have conducted expensive R&D concerning the development of automated construction technology will divulge sensitive information concerning their technologies. Furthermore,

those manufacturers involved in the development of such technologies may be legally obliged to not divulge such information.

It is essential for wide spread application of automated construction technologies, that a general cost and benefit database is constructed to allow potential investors to obtain information concerning the most likely estimates of associated costs and their potential volatility. The main benefit of financial risk analysis is that it facilitates the investigation of a range of possible outcomes, which is not possible with the deterministic appraisal methodologies.

5.15 Conclusions

This section presents the conclusions specific to the development of a generic financial risk analysis model for construction automation investment opportunities. From the results obtained, the following conclusions may be drawn.

1. Monte Carlo simulation has been successfully incorporated into a plant-hire appraisal model to perform probabilistic financial risk analysis for a hypothetical automated construction systems investment.
2. A total of 50000 iterations was shown to be sufficient for the probabilistic risk analysis model to achieve convergence.
3. The derivation of objective input parameter distributions using historical data is essential for refining and validating the generic financial risk analysis model presented for automated construction systems.

4. Historical mechatronics maintenance data is required to determine the maintenance characteristics of the existing technologies.
5. For the subjectively assessed parameters used in the present research, the normal, triangular, uniform and discrete distribution functions provide similar predictions for investment NPV risk. However, the uniform distribution overestimates the probability of extreme values and, subsequently, provides over conservative results.
6. The simulation results are dependant upon the shape of the input distribution, the manner of setting the mean and standard deviation and the correlation between each input parameter. However, the choice of distribution type is insignificant in relation to the subjective estimation of input parameter variables.
7. The upper limits for hourly hire rates must be set in relation to the task undertaken by the machine and the total hourly cost of the task using traditional techniques and human operatives.
8. Automated construction systems investment is sensitive to the rate of interest, the residual value of the machine, maintenance costs and the growth in maintenance costs as the machine nears to end of it's functional life.
9. Cheap sources of finance must be made available to investors in automated systems in order to stimulate further R&D, investment and widespread adoption of innovative construction plant and machinery.

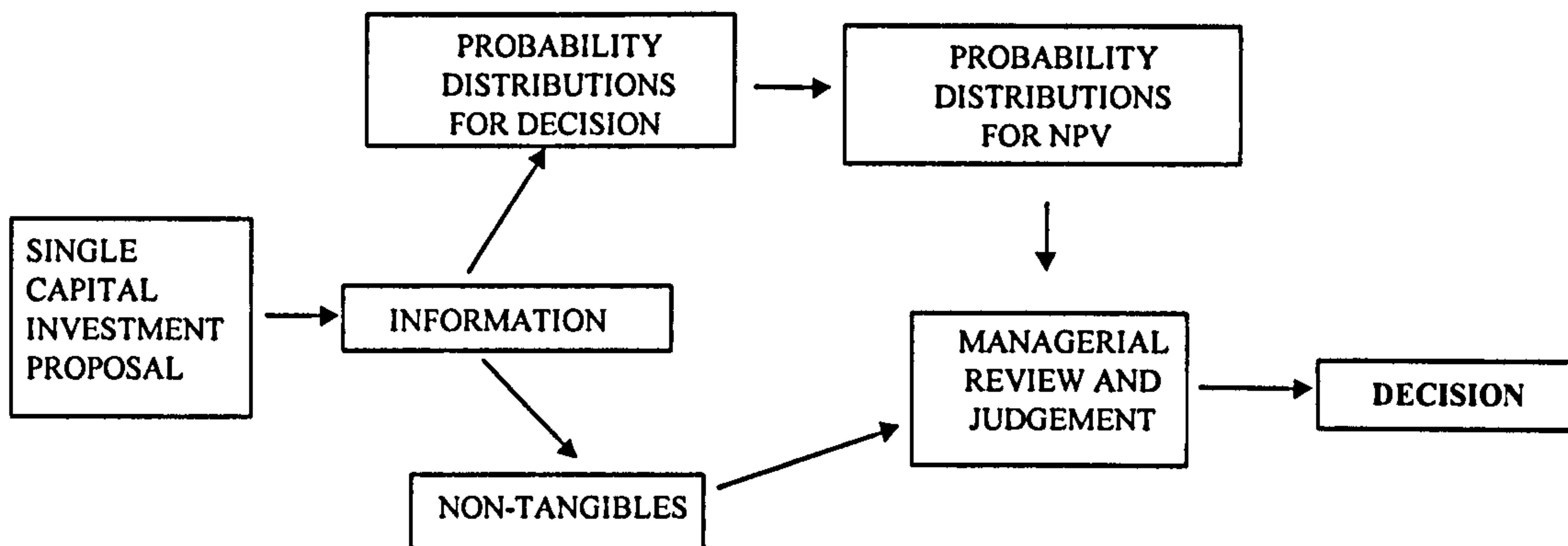


Figure 5.1: The risk analysis process
Source: Hertz (1983)

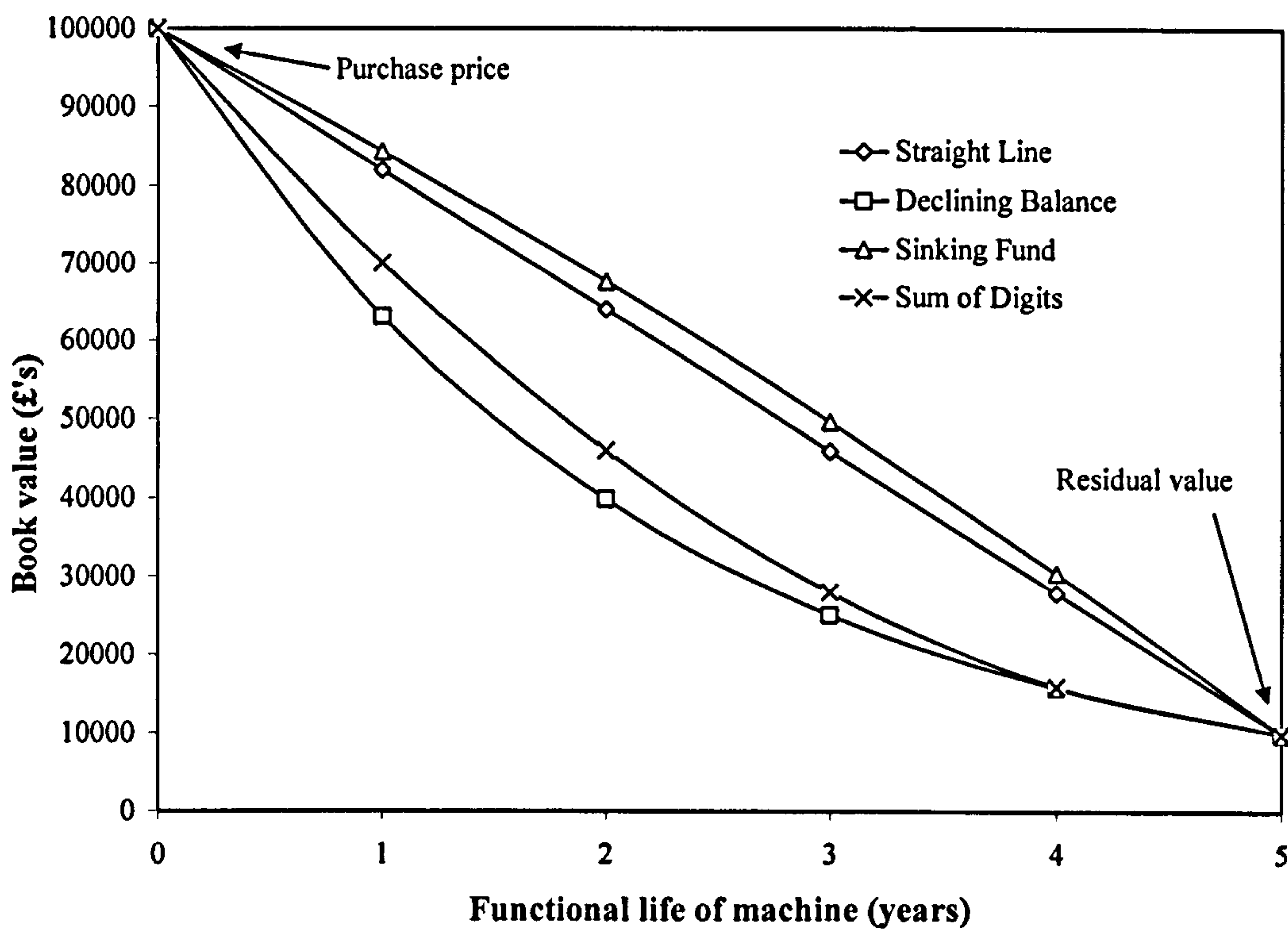


Figure 5.2: Graphical comparison of alternative methods of depreciation

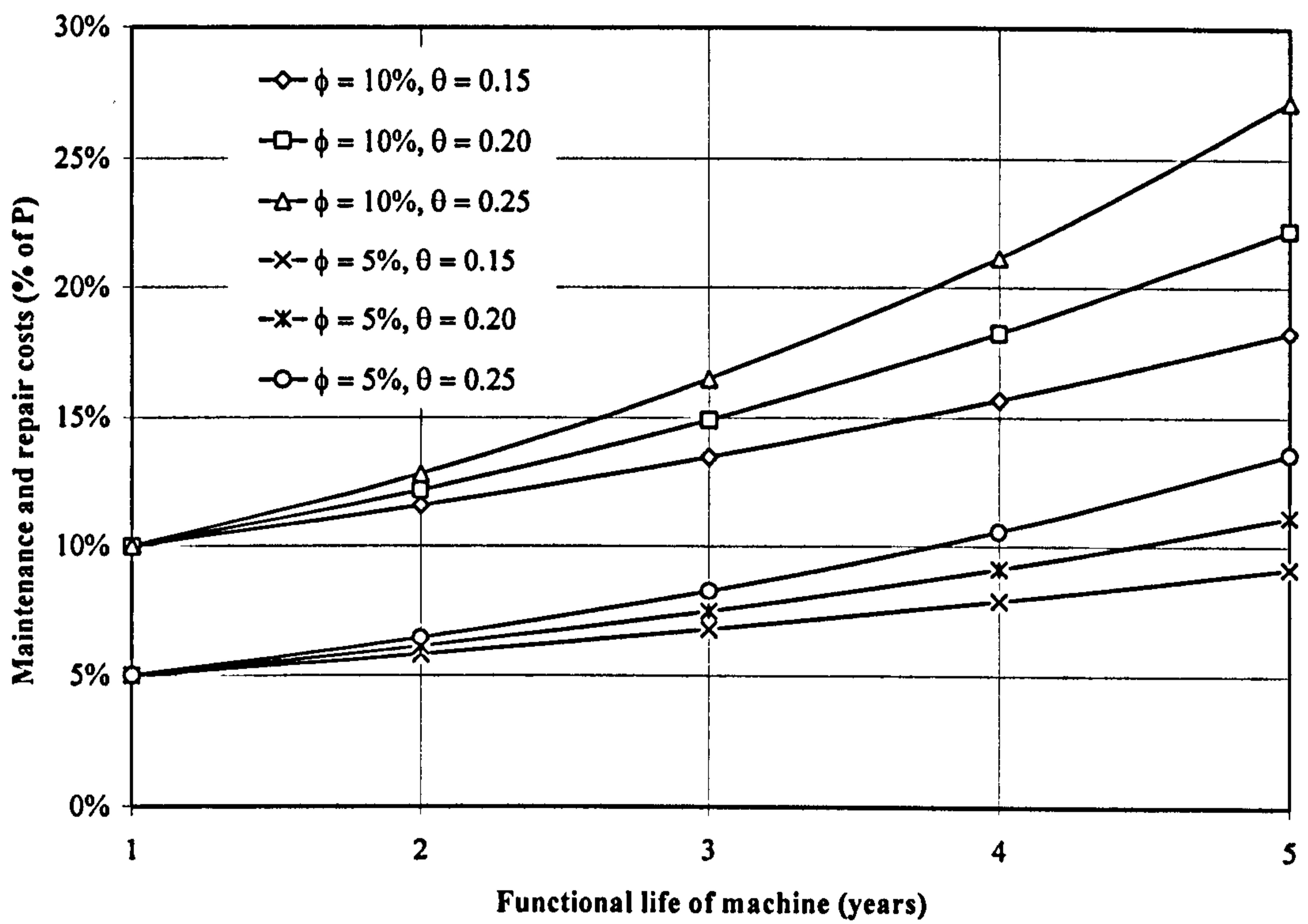


Figure 5.3: Comparison of alternative maintenance cost growth rates

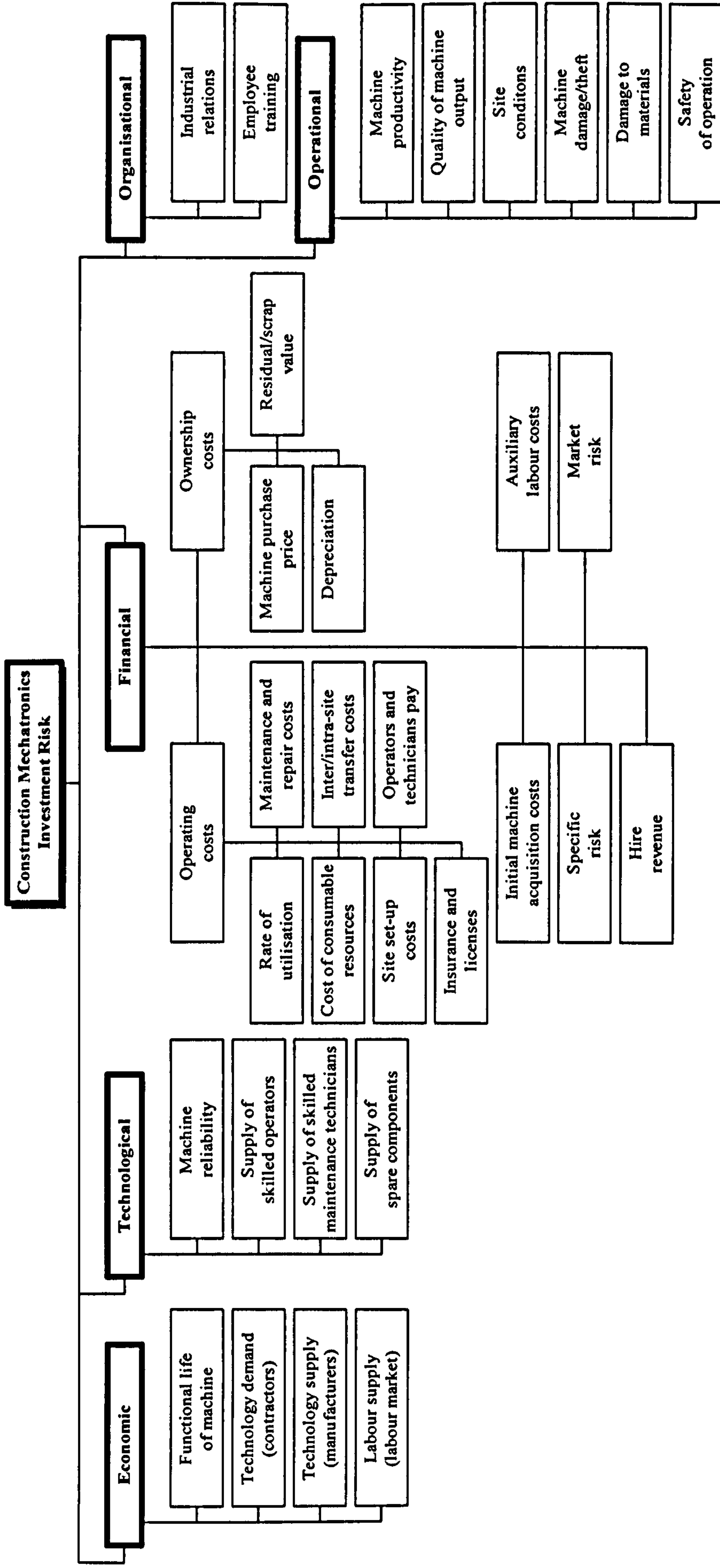


Figure 5.4: Taxonomy of construction mechatronics investment risk

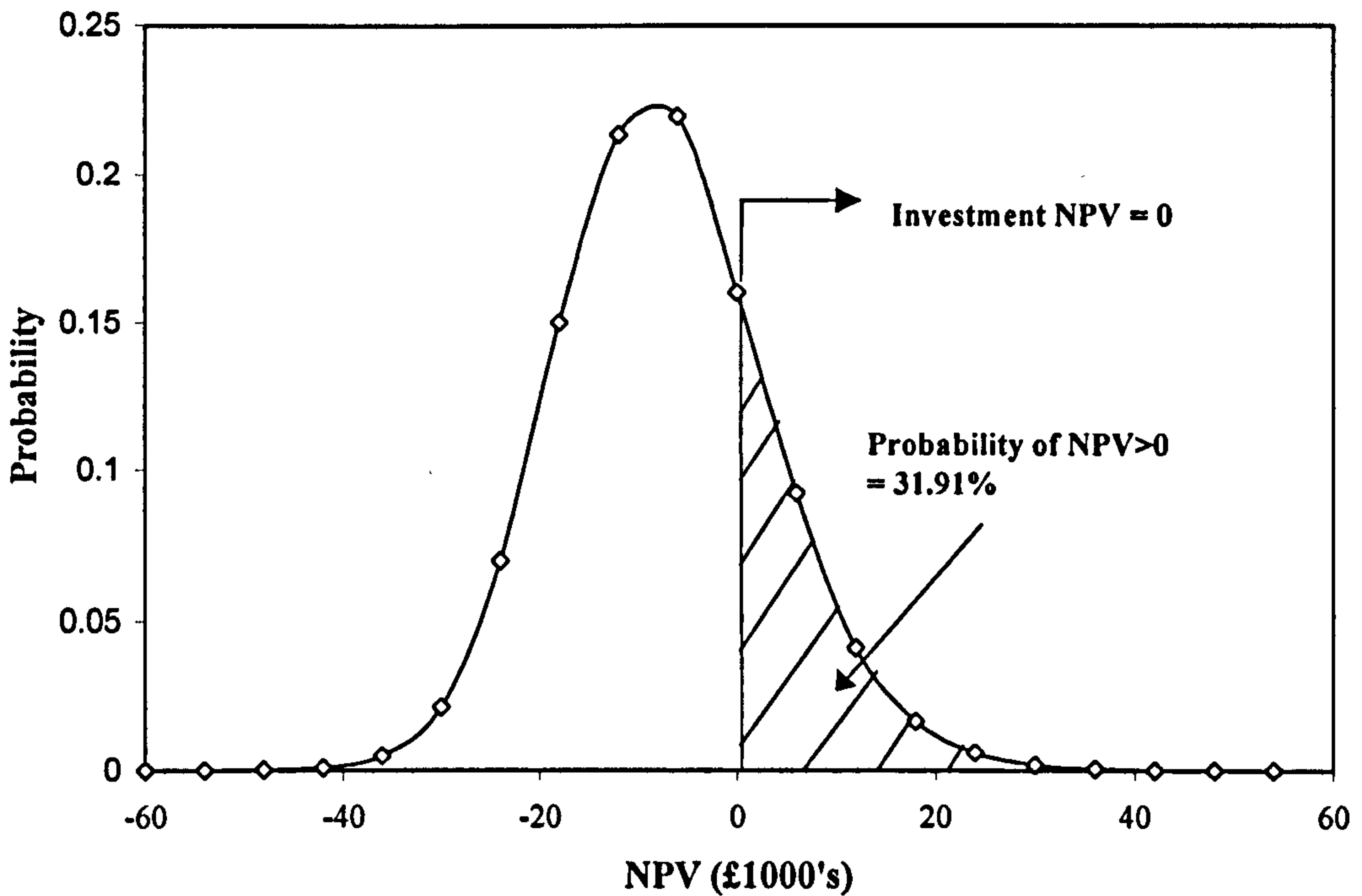


Figure 5.5: Distribution of investment NPV showing up-side investment potential

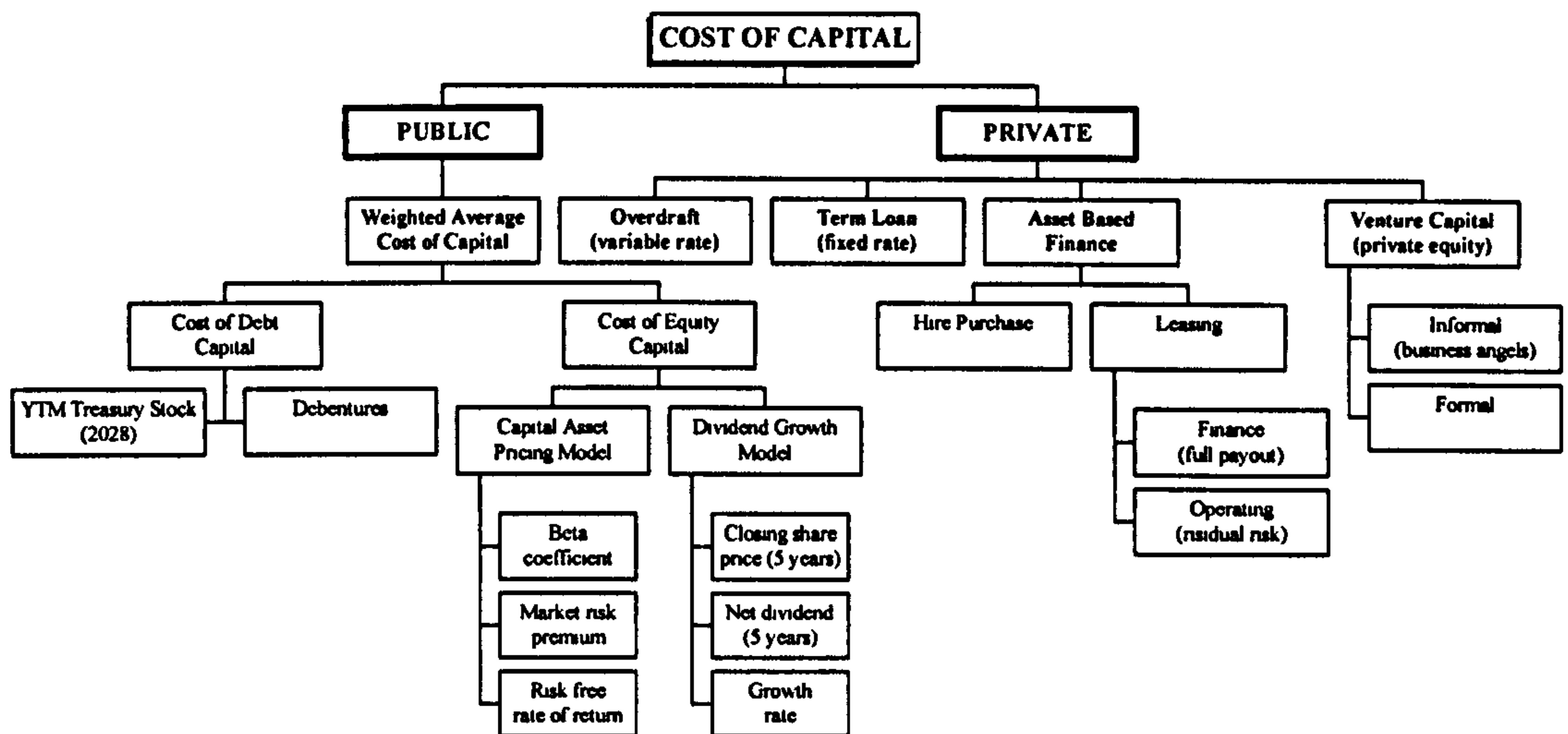


Figure 5.6: Methods of determining the cost of capital

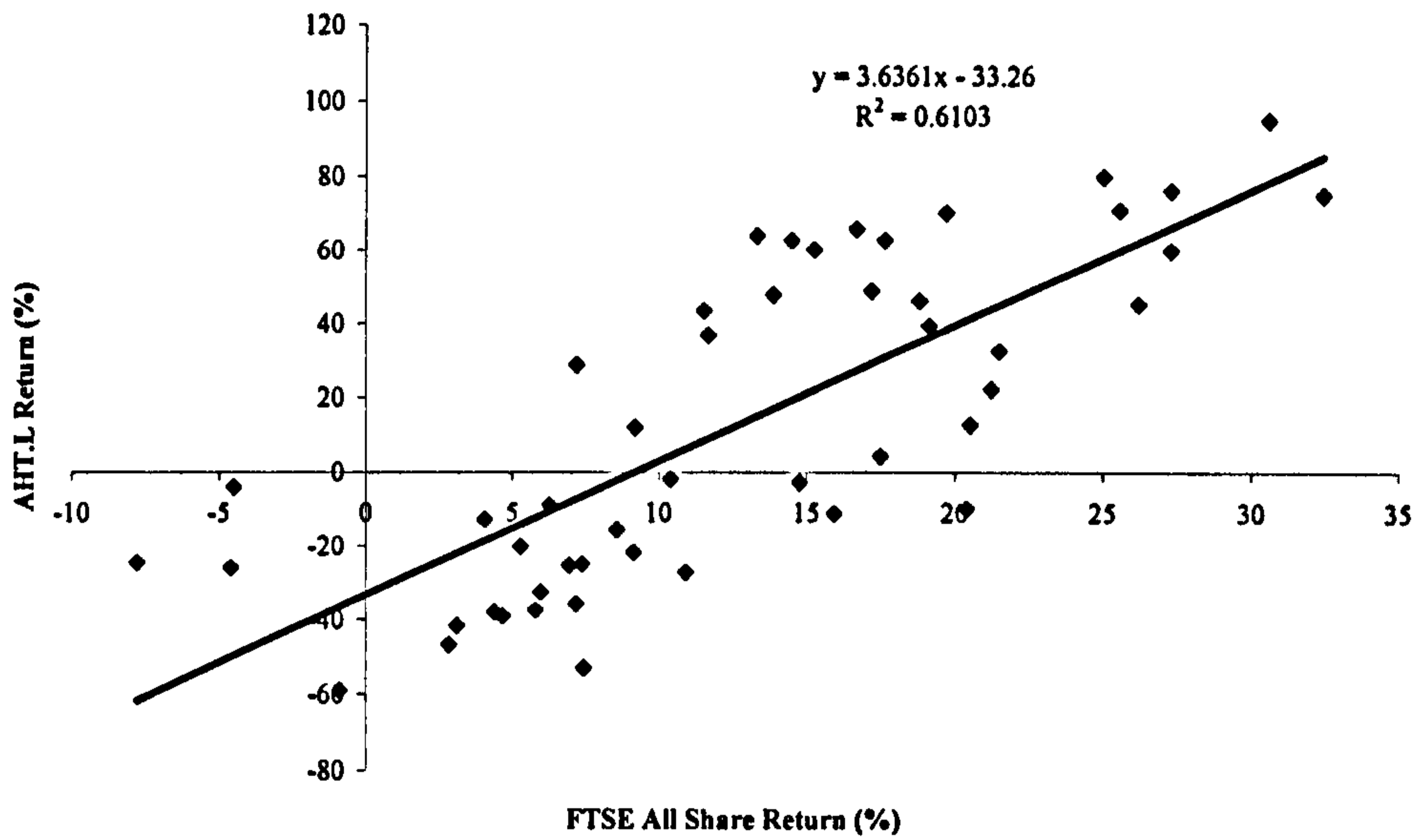


Figure 5.7: UK plant hire firm market model, 1995 to 2000
 Source: Market Eye historical equity data, September 2000

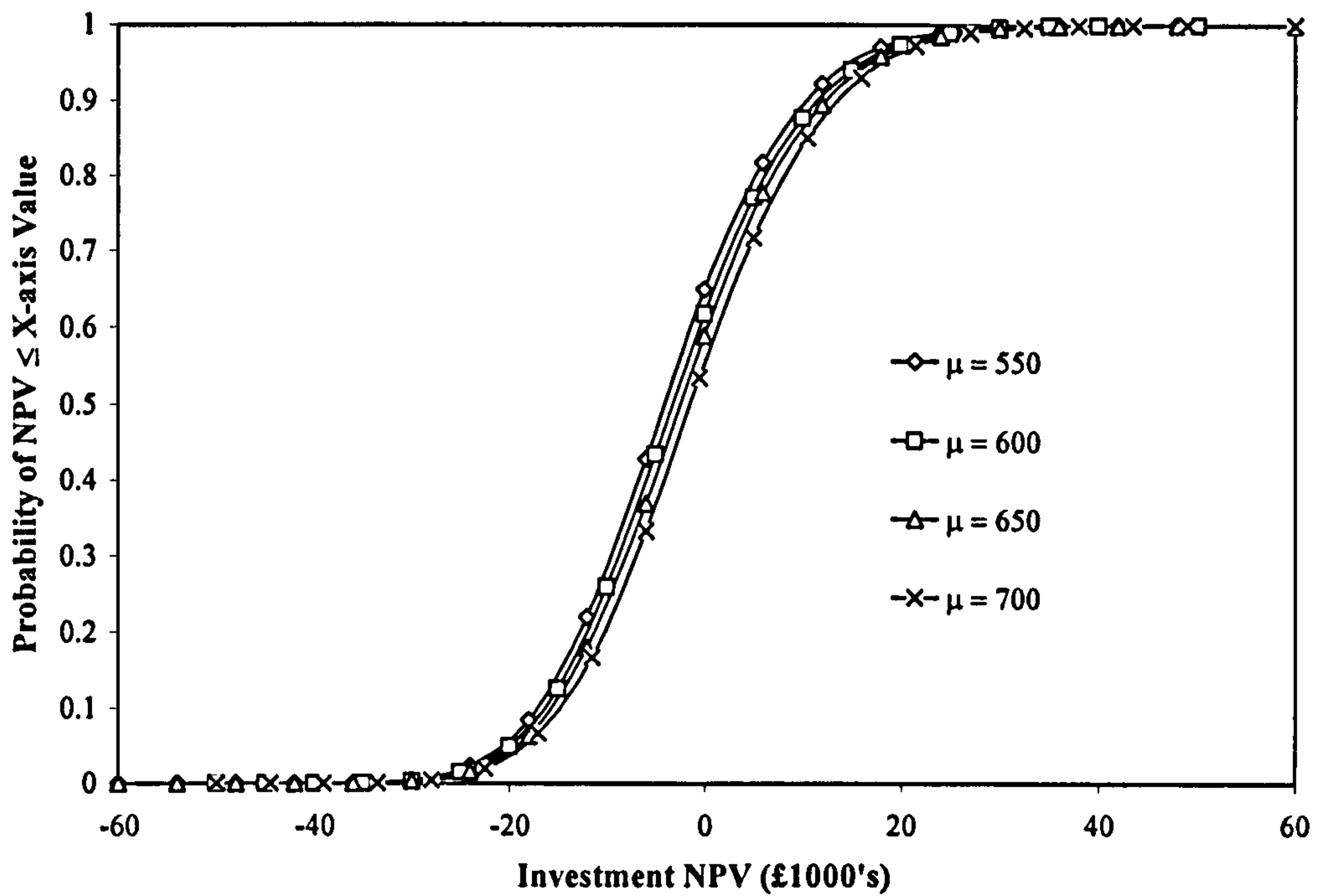


Figure 5.8: The effect of varying the mean cost of inter-site transfers (C_t)

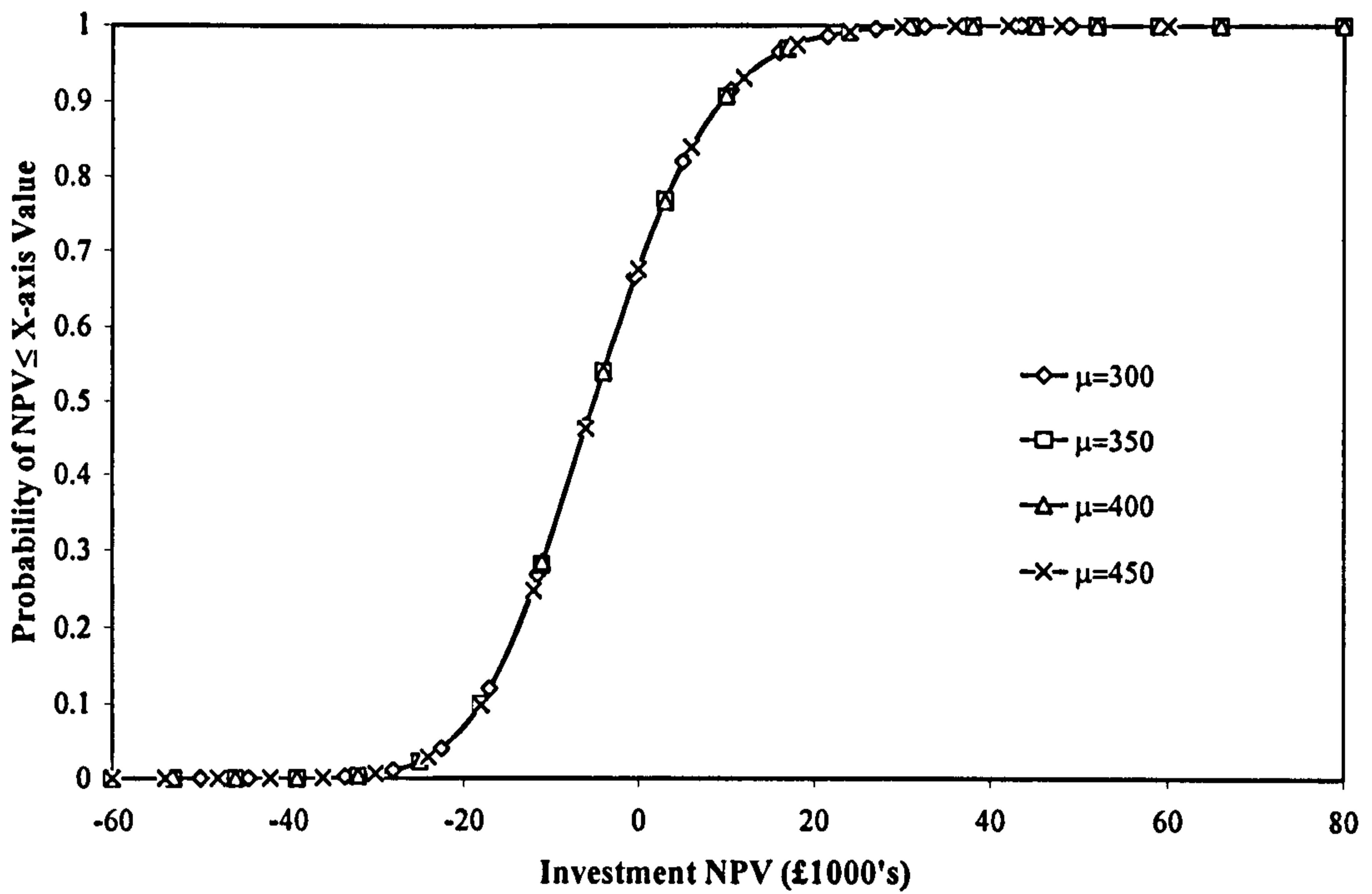


Figure 5.9: The effect of varying the mean cost of operating licenses (I)

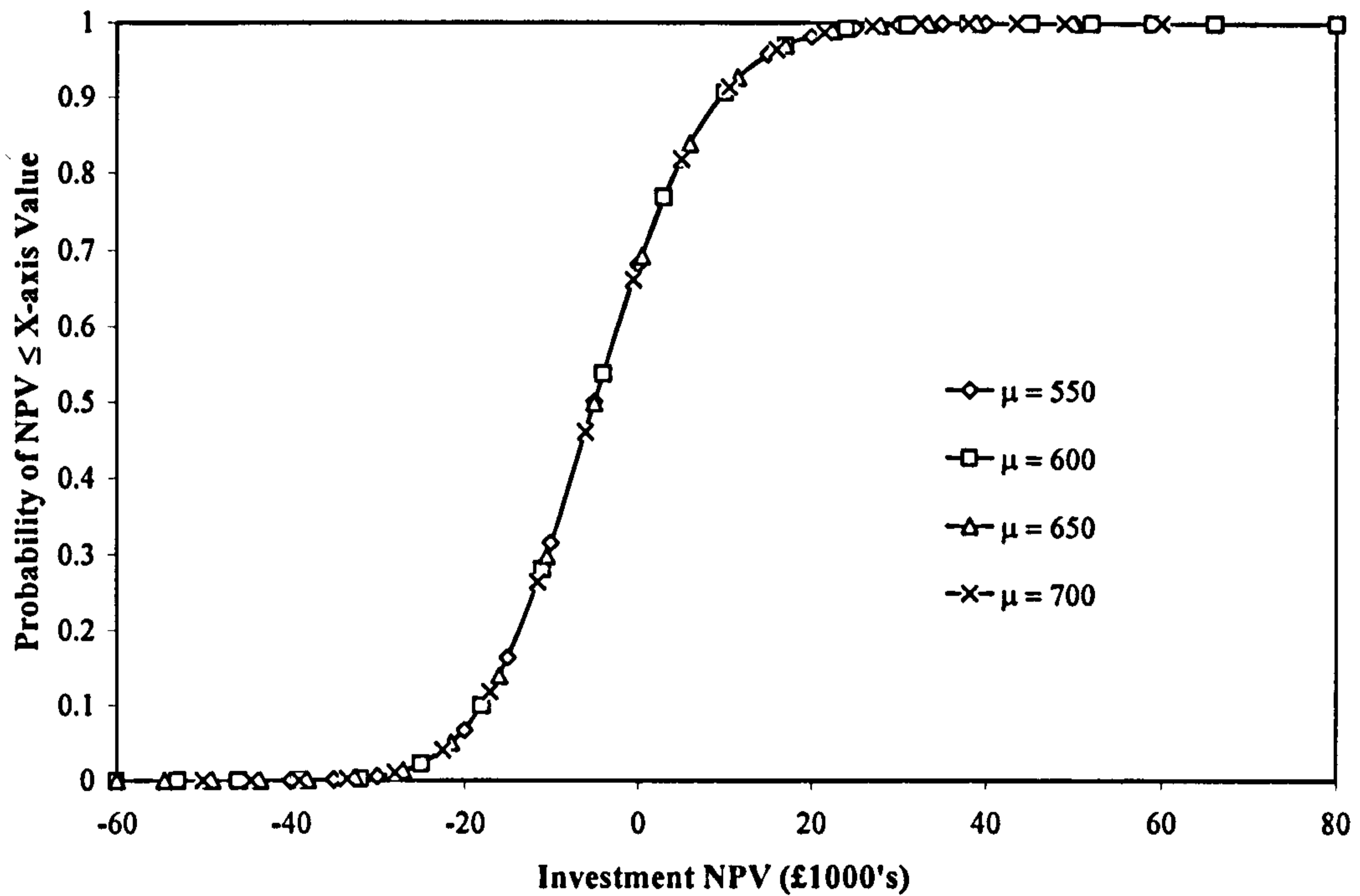


Figure 5.10: The effect of varying the mean cost of insurance premiums (I)

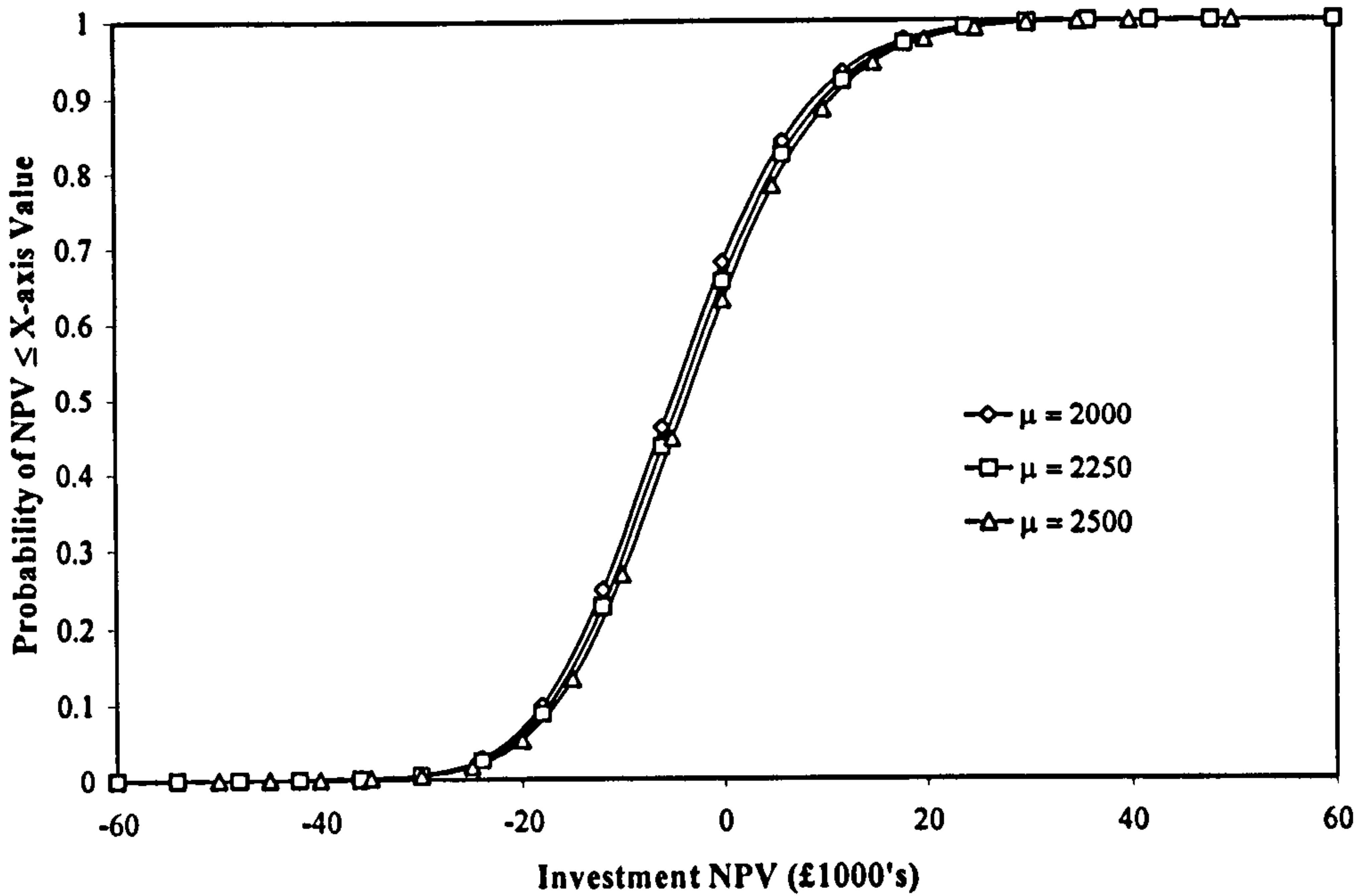


Figure 5.11: The effect of varying the total hours utilised per annum (H_{yr})

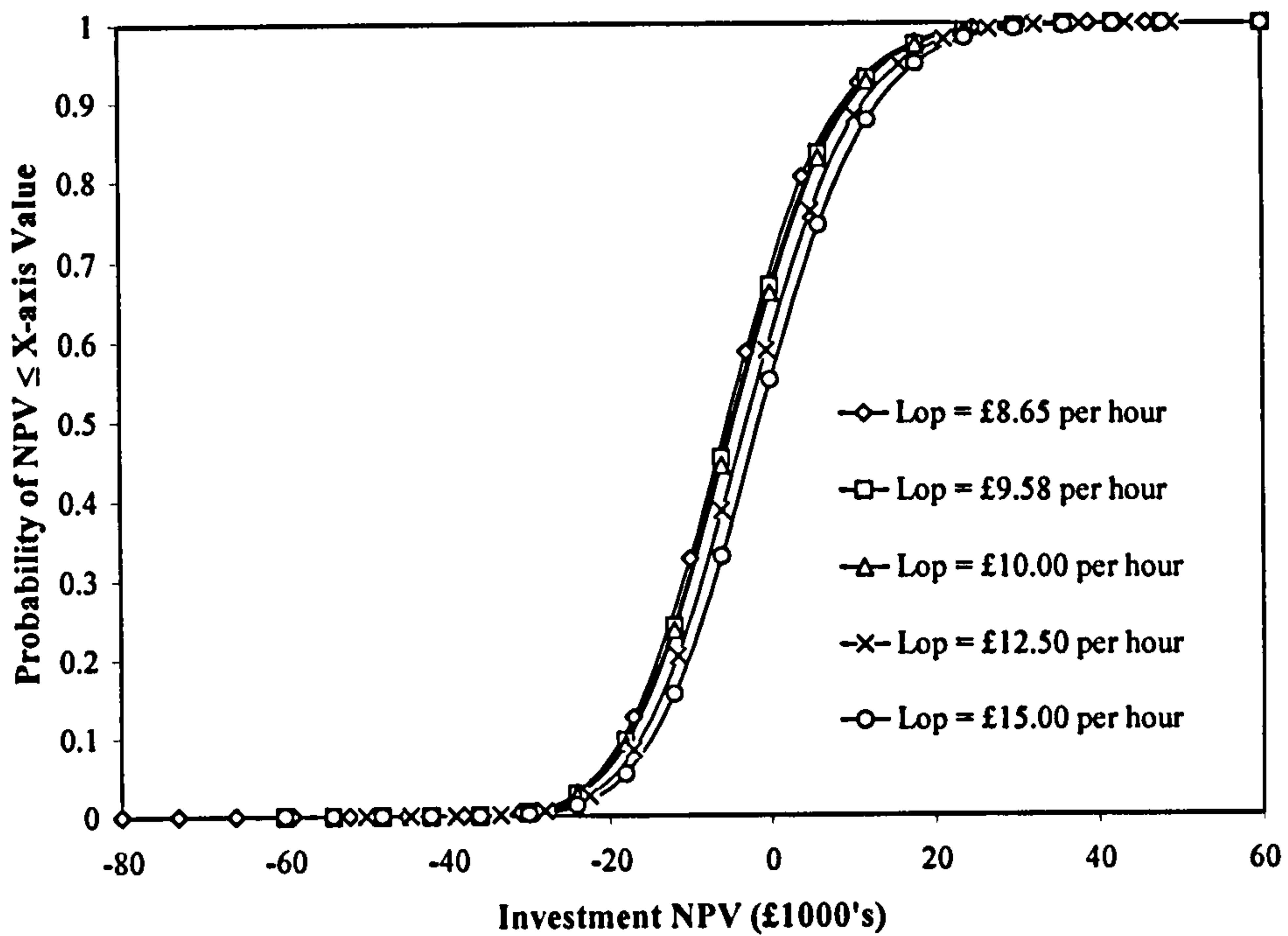


Figure 5.12: The effect of varying the operators rate of pay (L_{op})

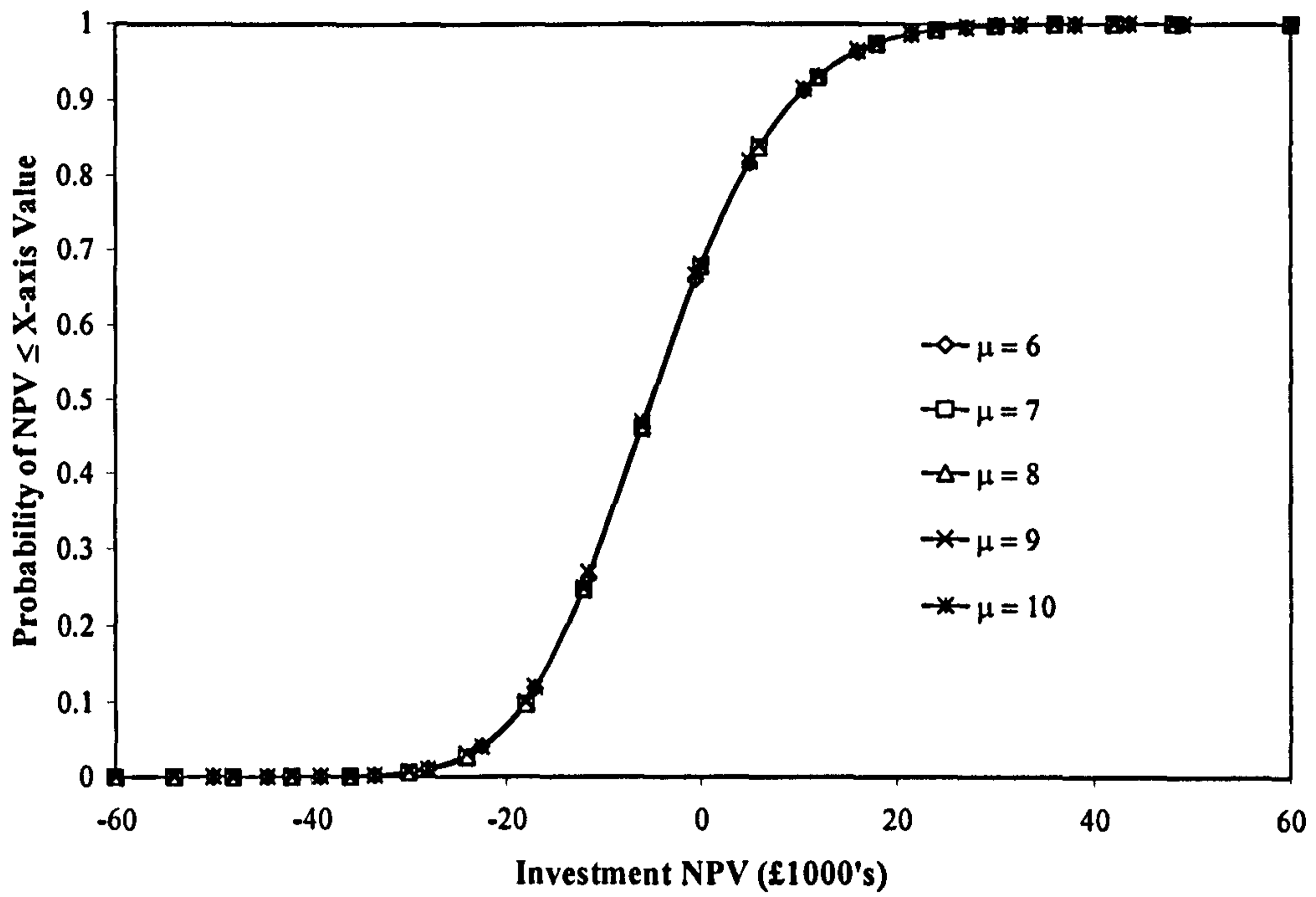


Figure 5.13: The effect of varying the mean hours utilised per day (H_{day})

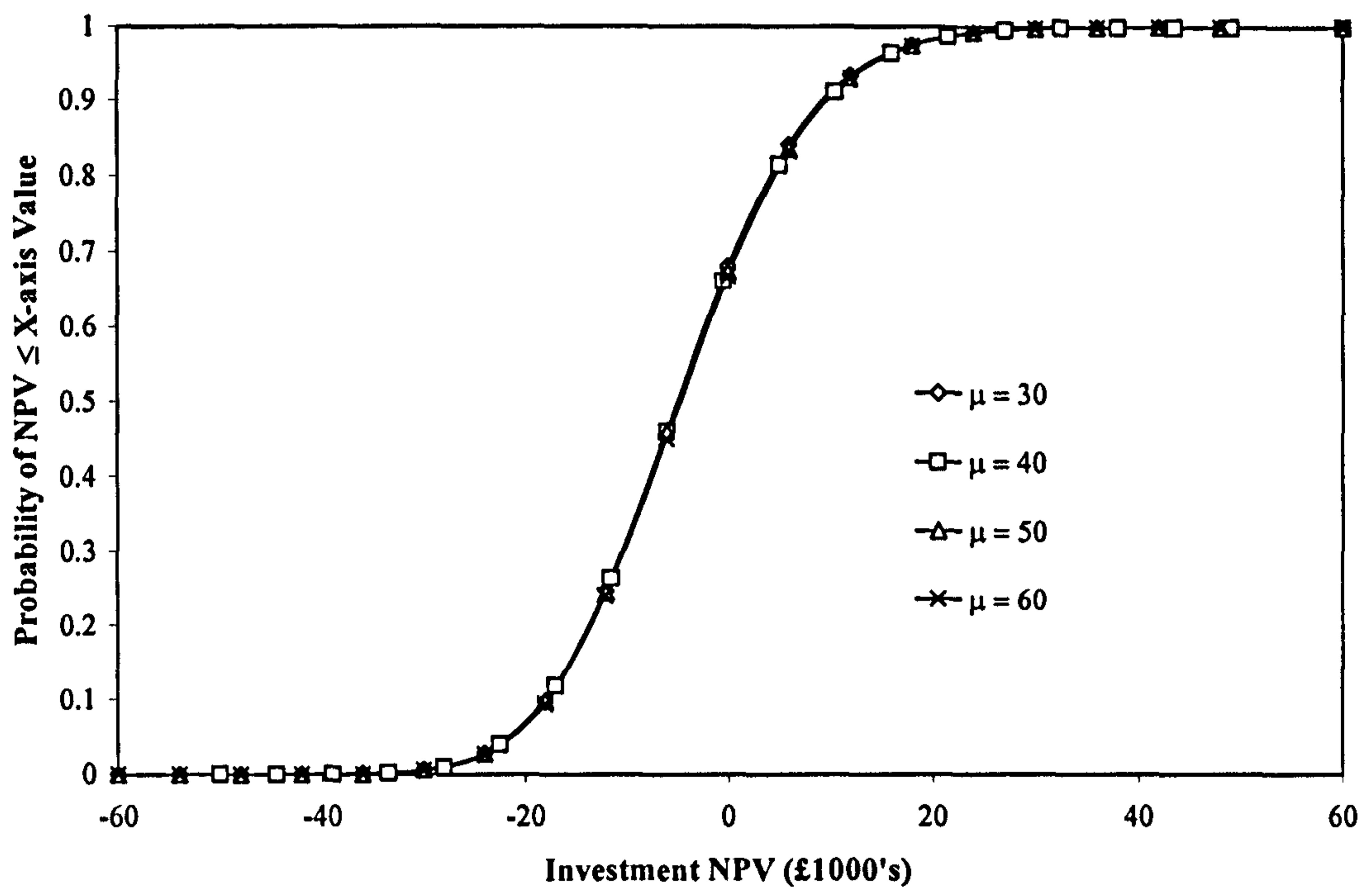


Figure 5.14: The effect of varying the mean routine maintenance period (M_t)

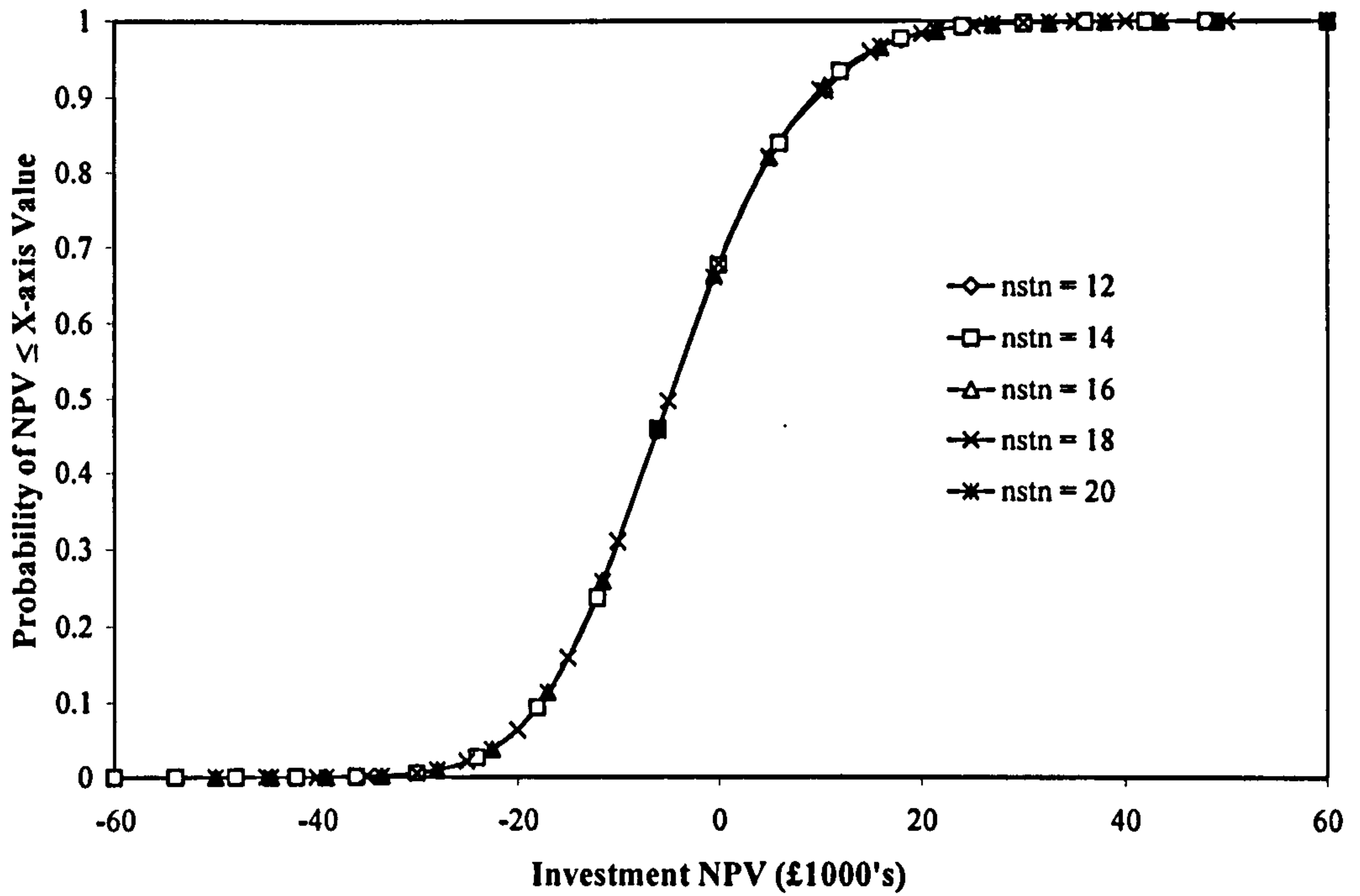


Figure 5.15: The effect of varying the total number of work stations per site (n_{stn})

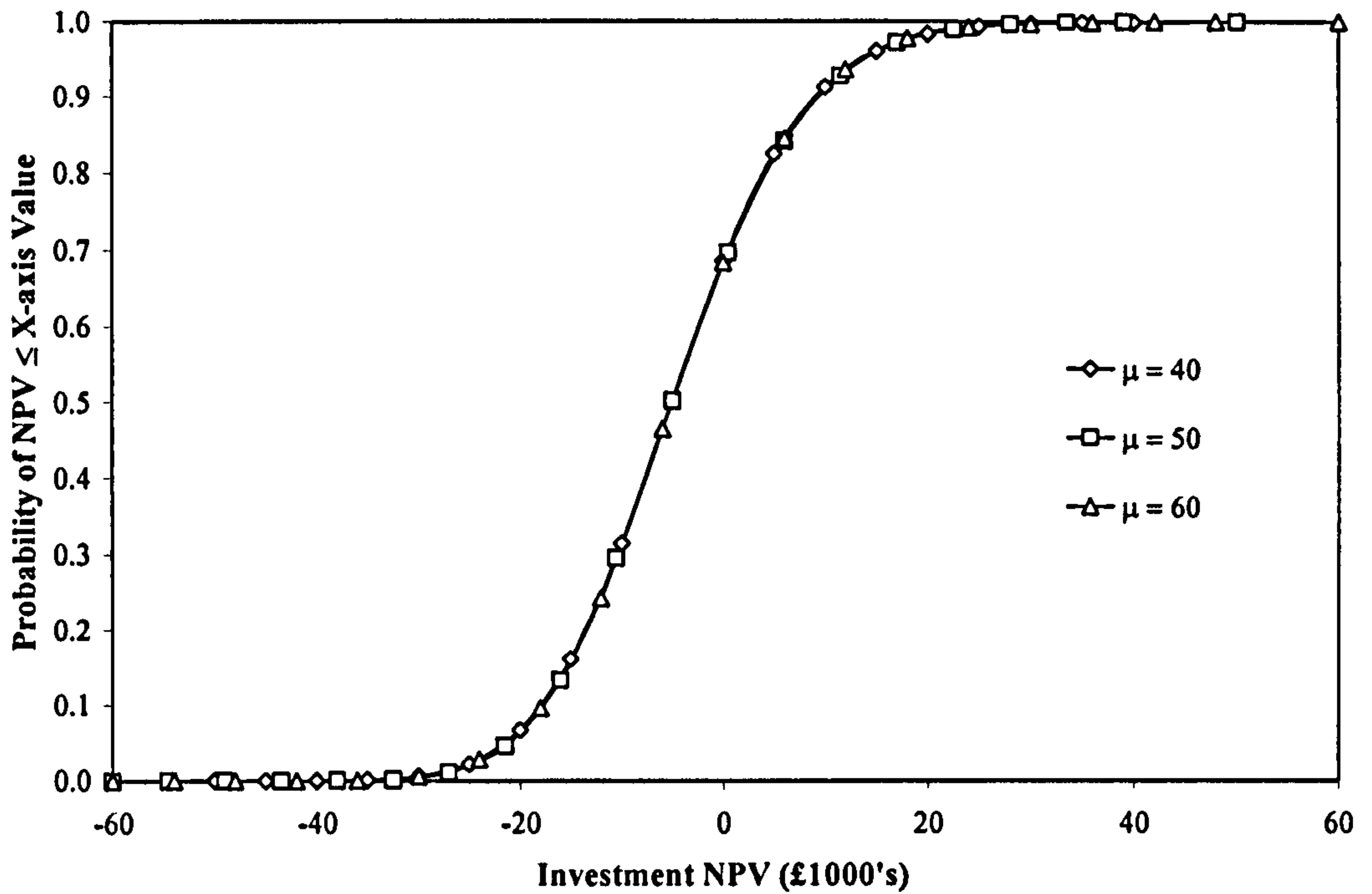


Figure 5.16: The effect of varying the work station transfer period (H_{stn})

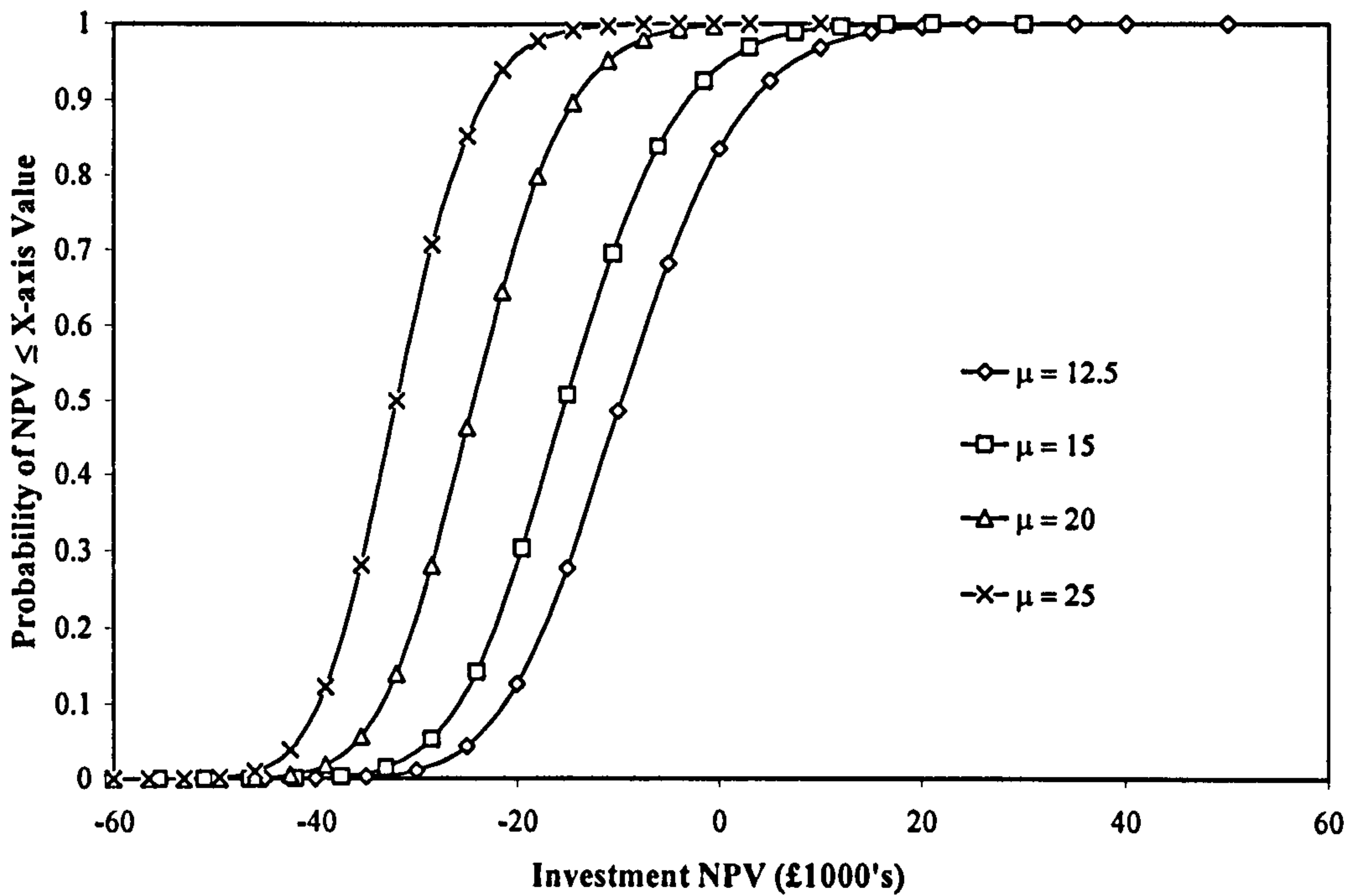


Figure 5.17: The effect of varying the cost of capital (i)

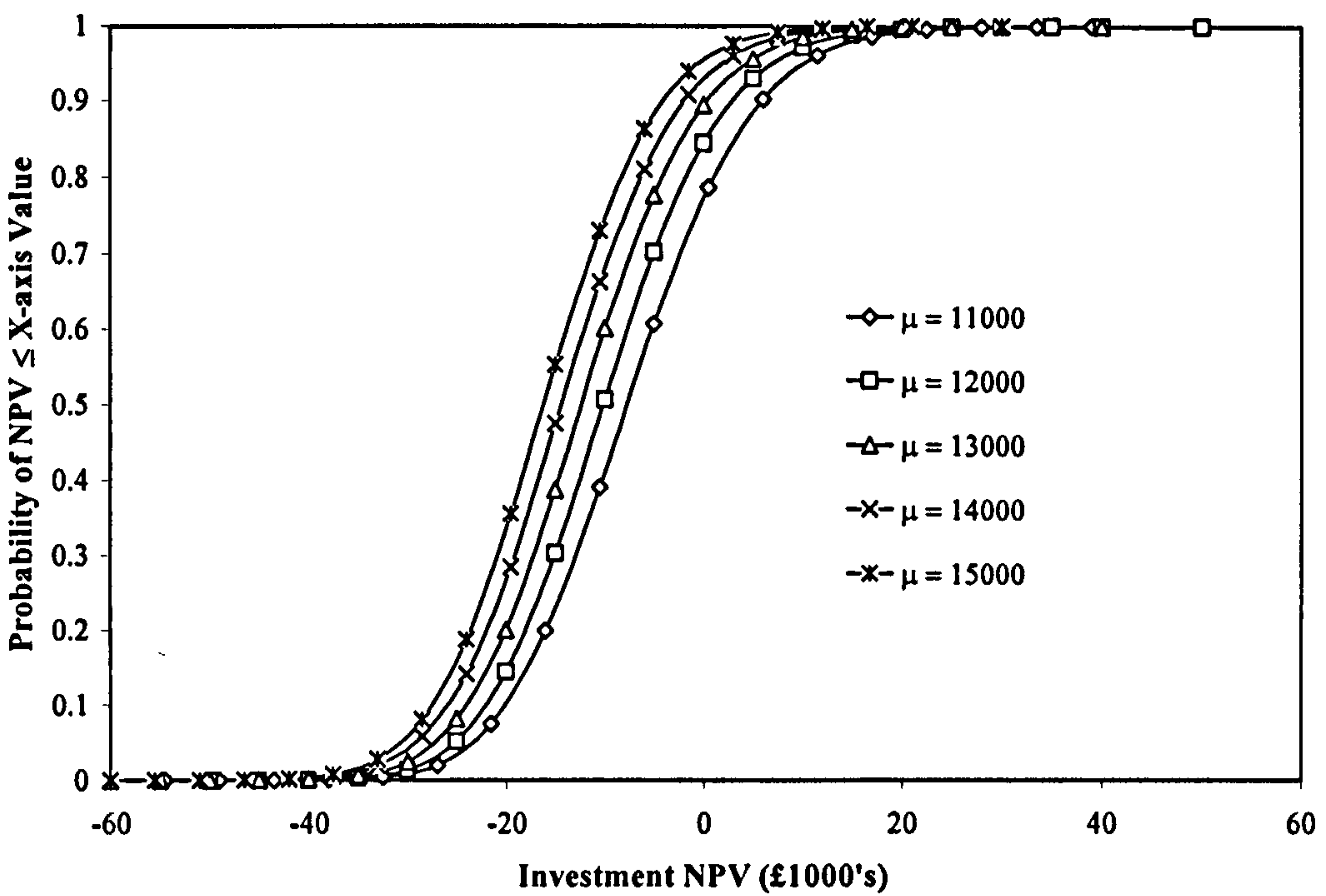


Figure 5.18: The effect of varying the residual machine value (S_r)

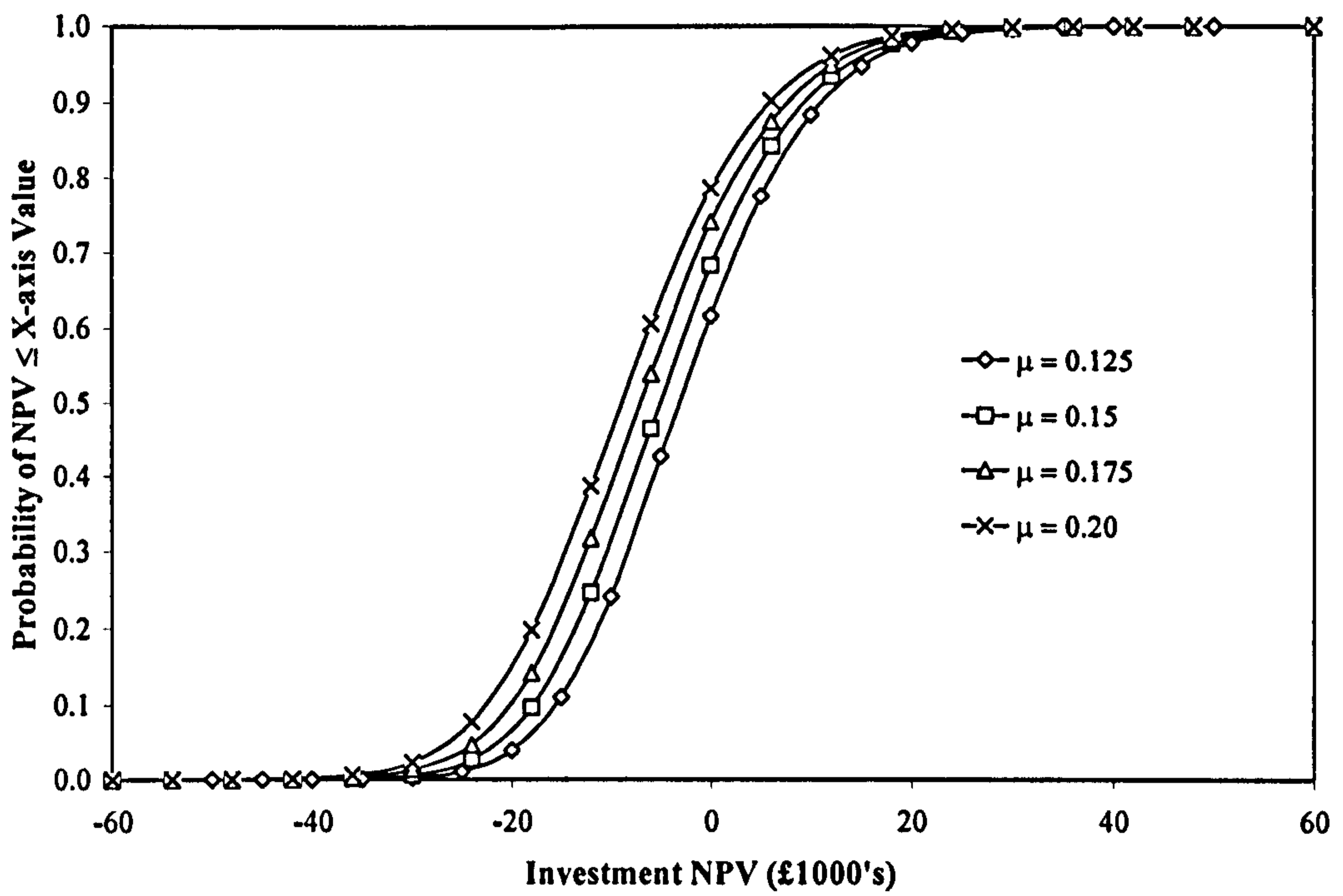


Figure 5.19: The effect of varying the scheduled maintenance costs (Φ)

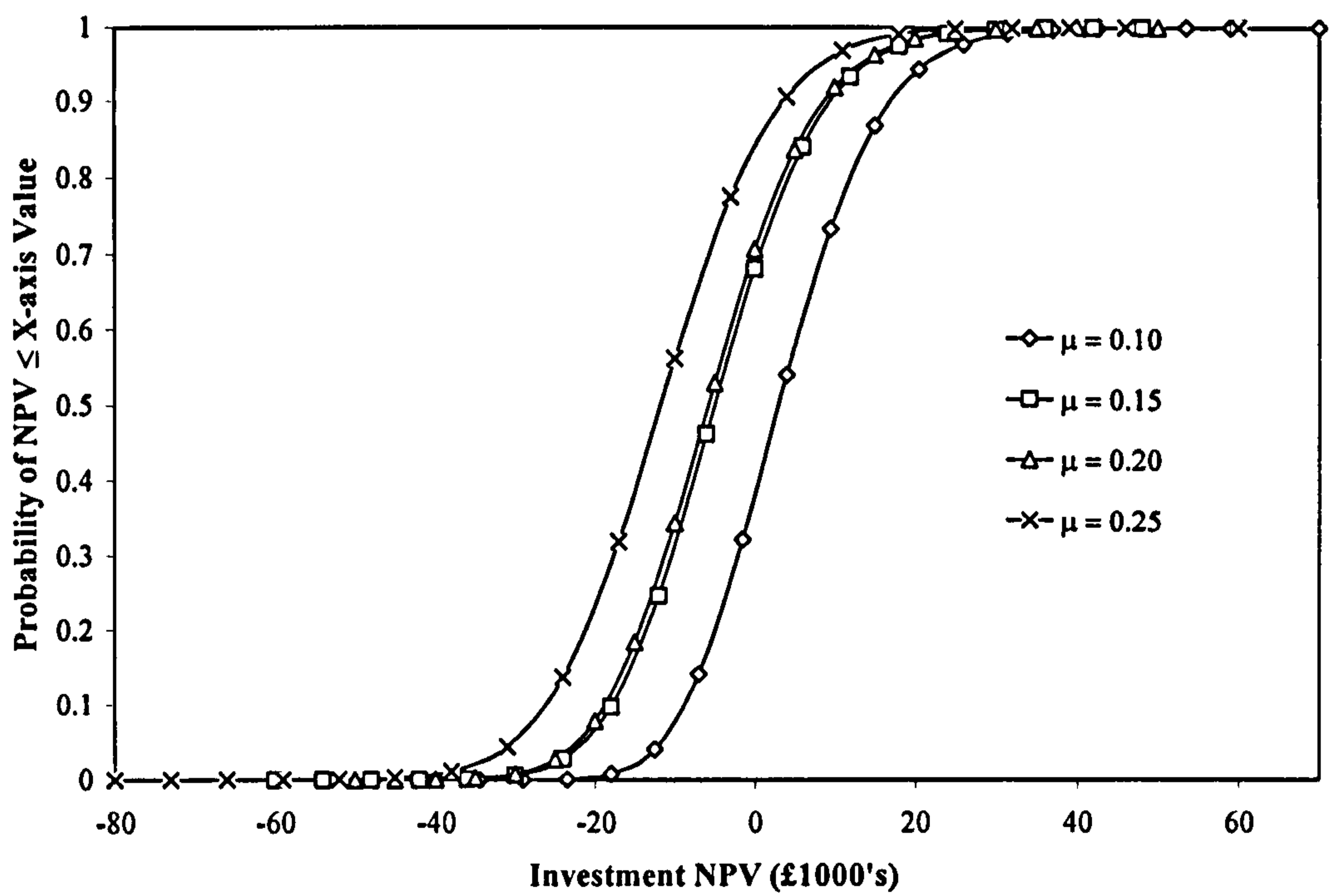


Figure 5.20: The effect of varying the growth of scheduled maintenance costs (θ)

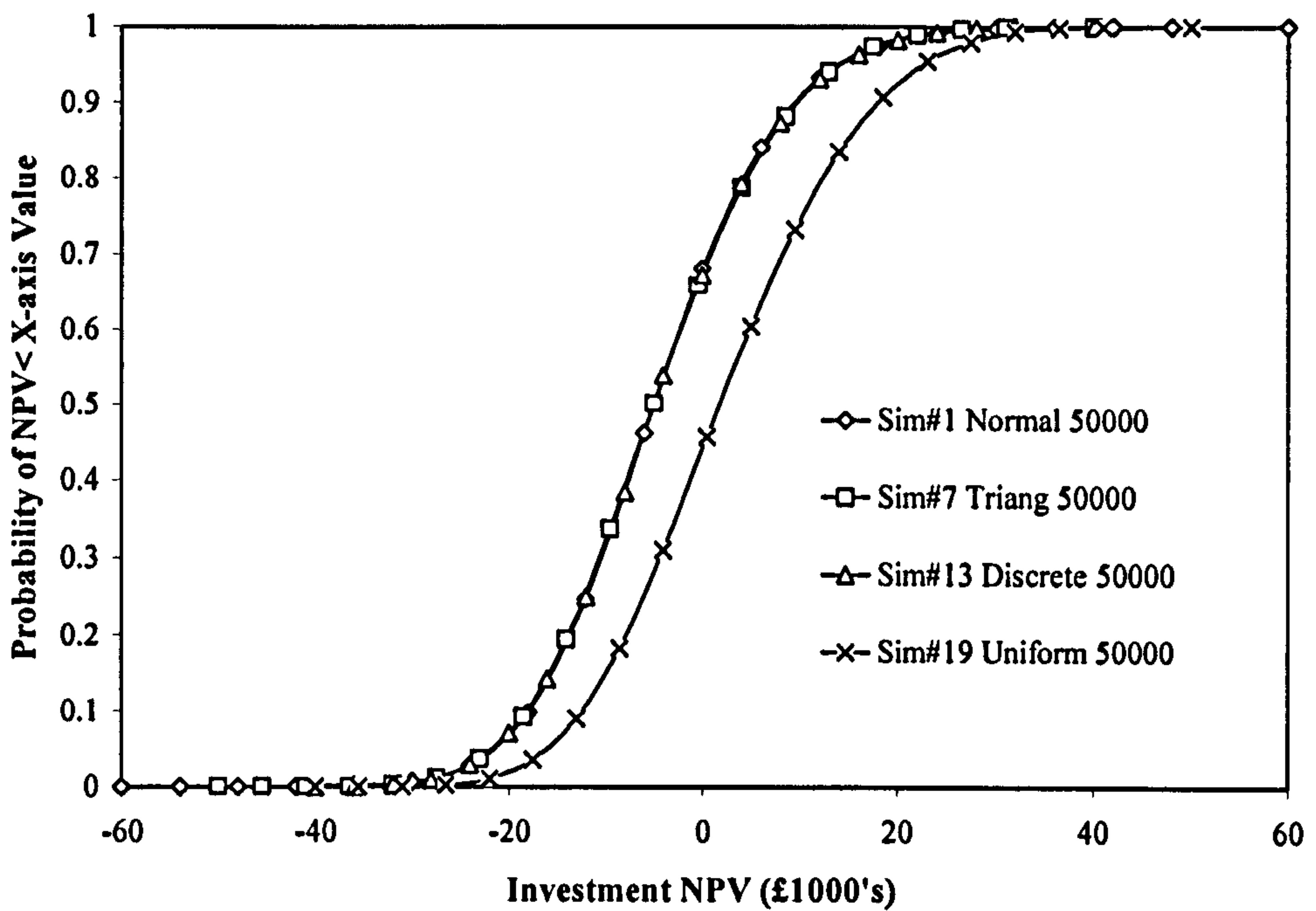


Figure 5.21: Comparison of different input distributions (50000 iterations)

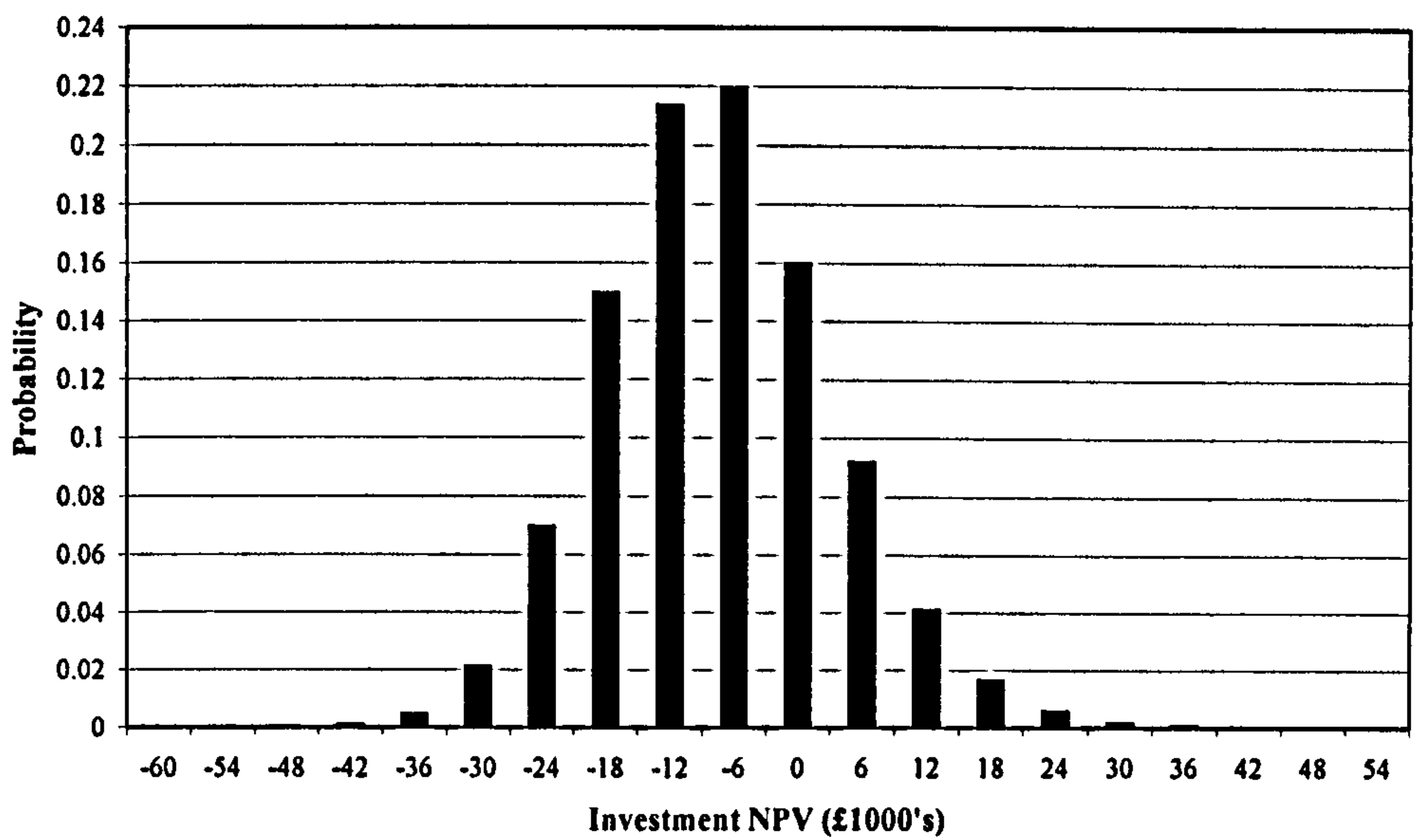


Figure 5.22: Probability distribution of NPV for 50000 iterations (normal)

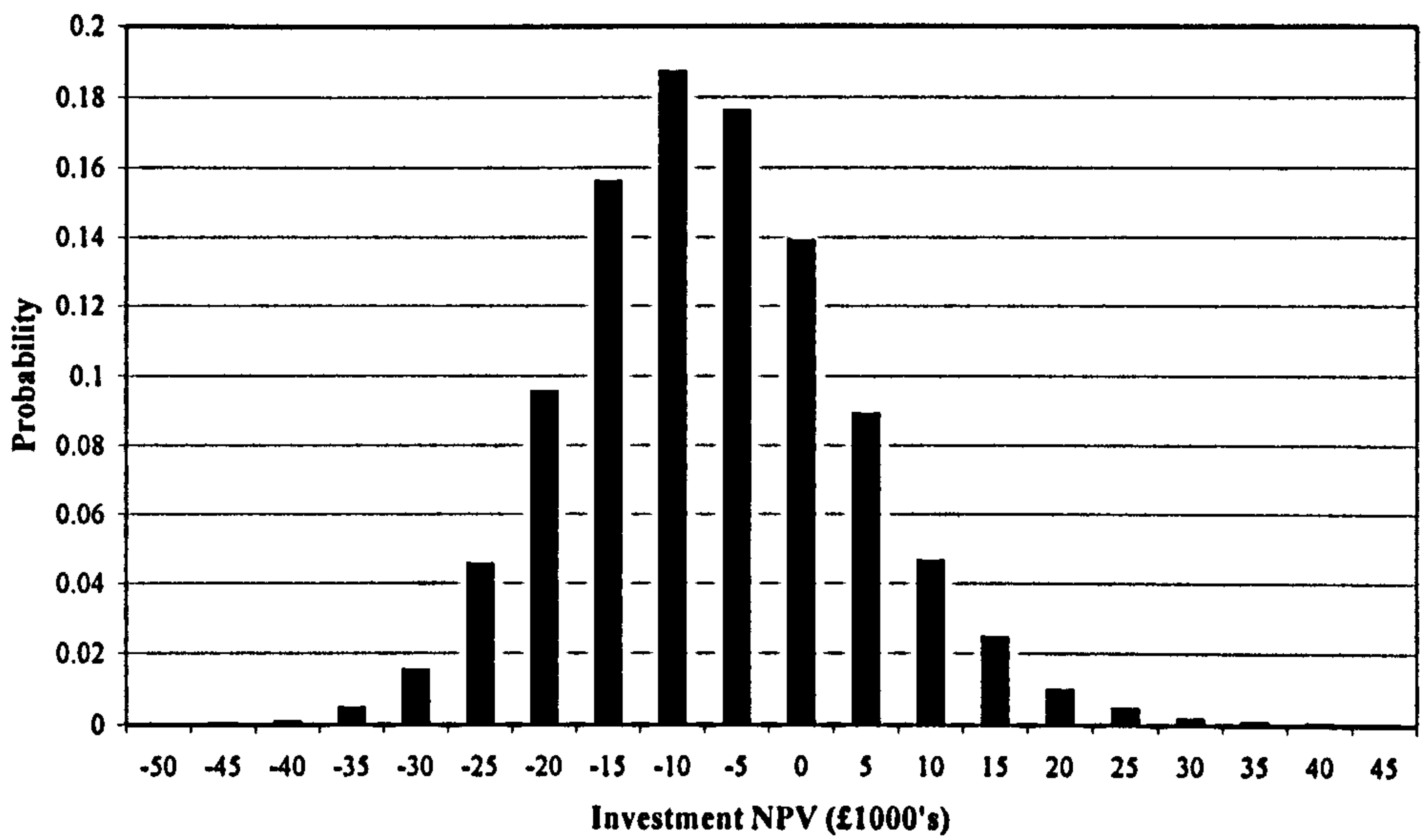


Figure 5.23: Probability distribution of NPV for 25000 iterations (normal)

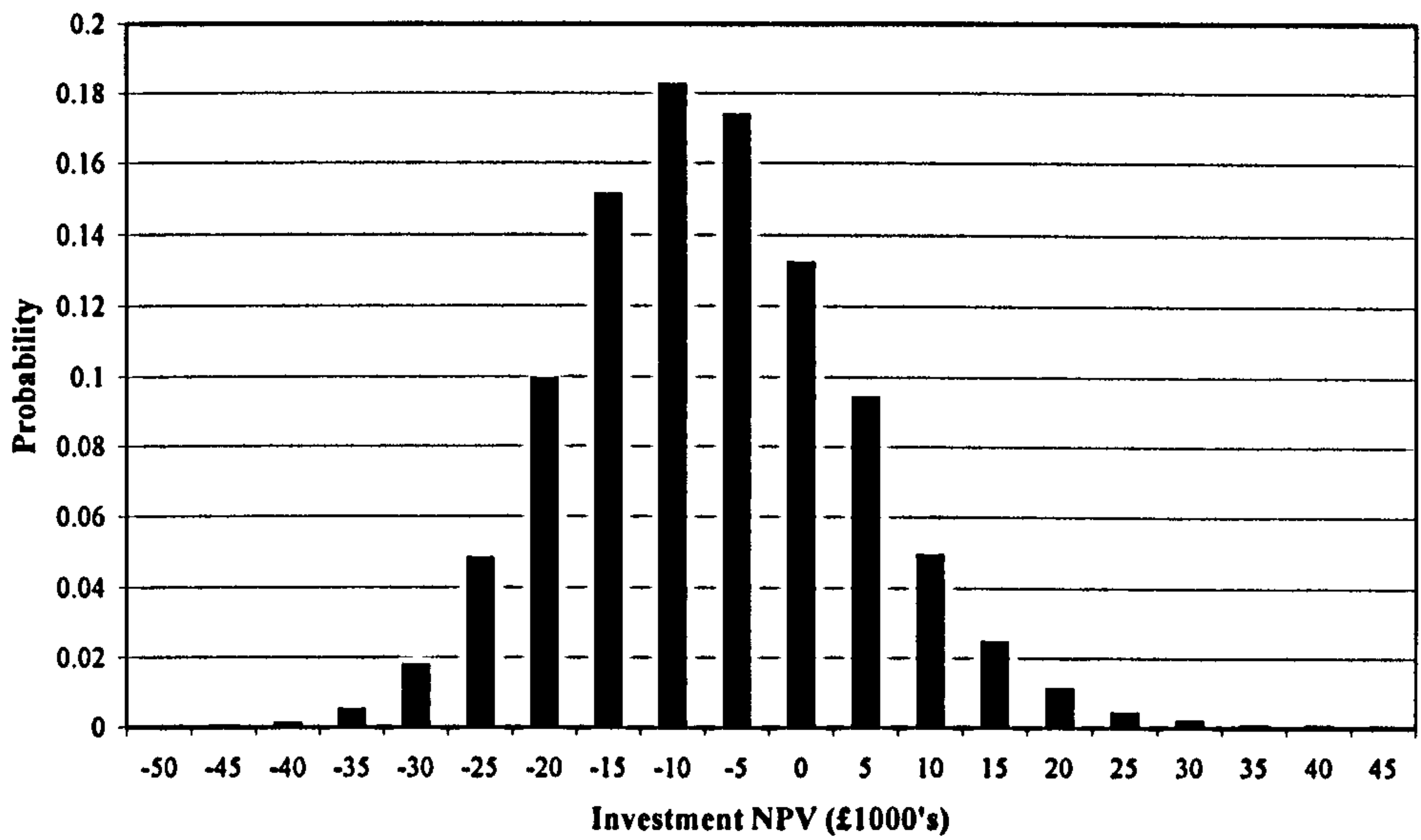


Figure 5.24: Probability distribution of NPV for 10000 iterations (normal)

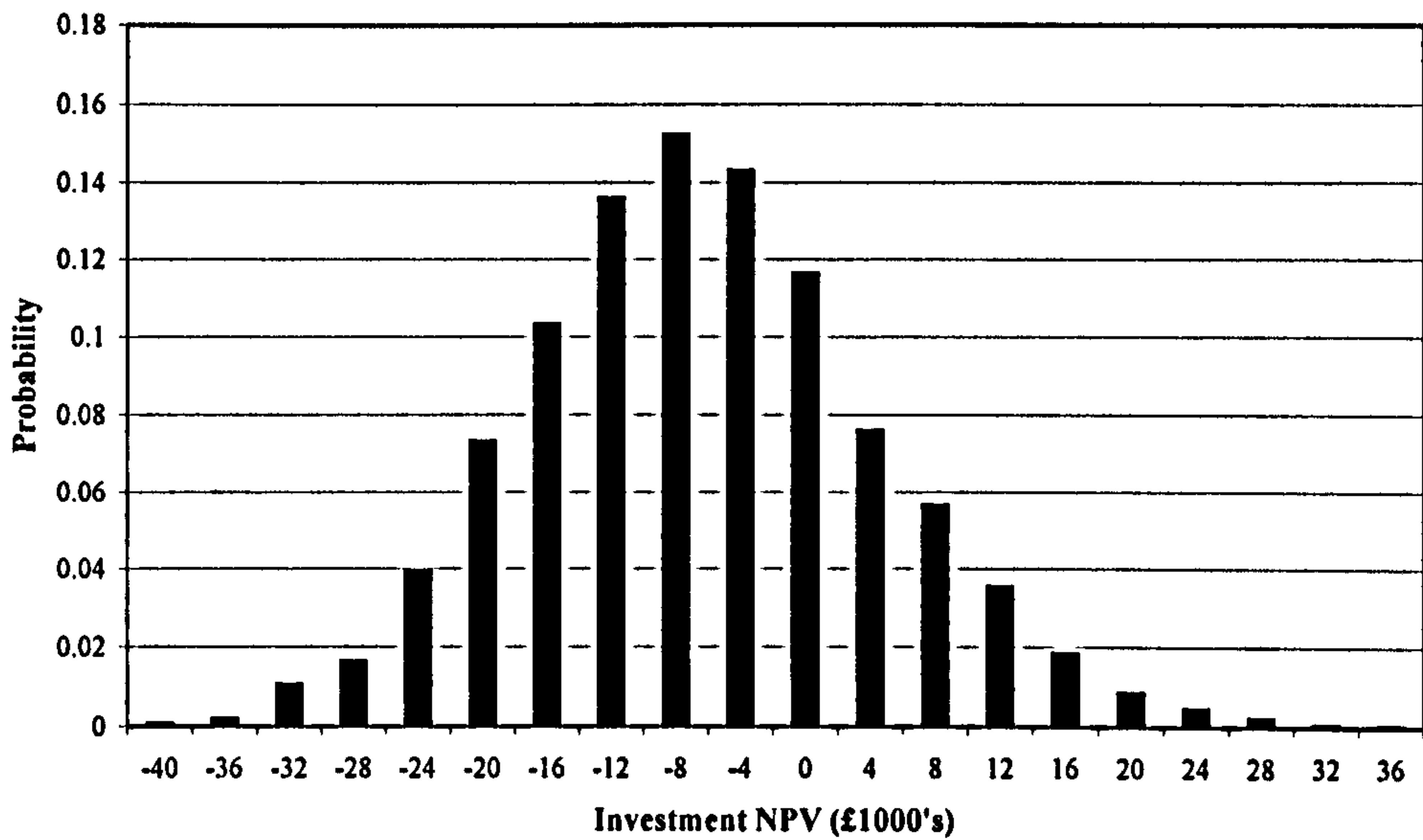


Figure 5.25: Probability distribution of NPV for 5000 iterations (normal)

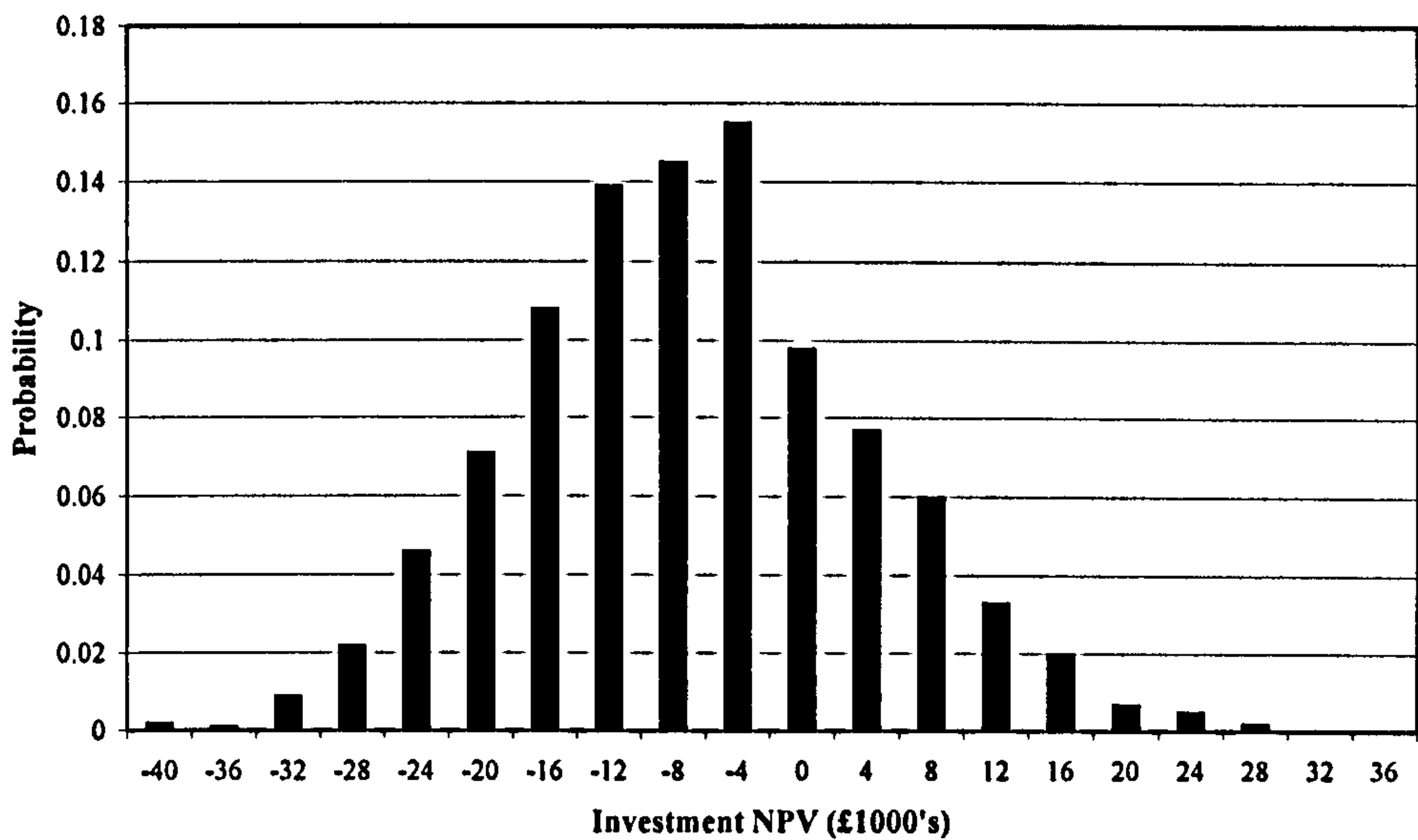


Figure 5.26: Probability distribution of NPV for 1000 iterations (normal)

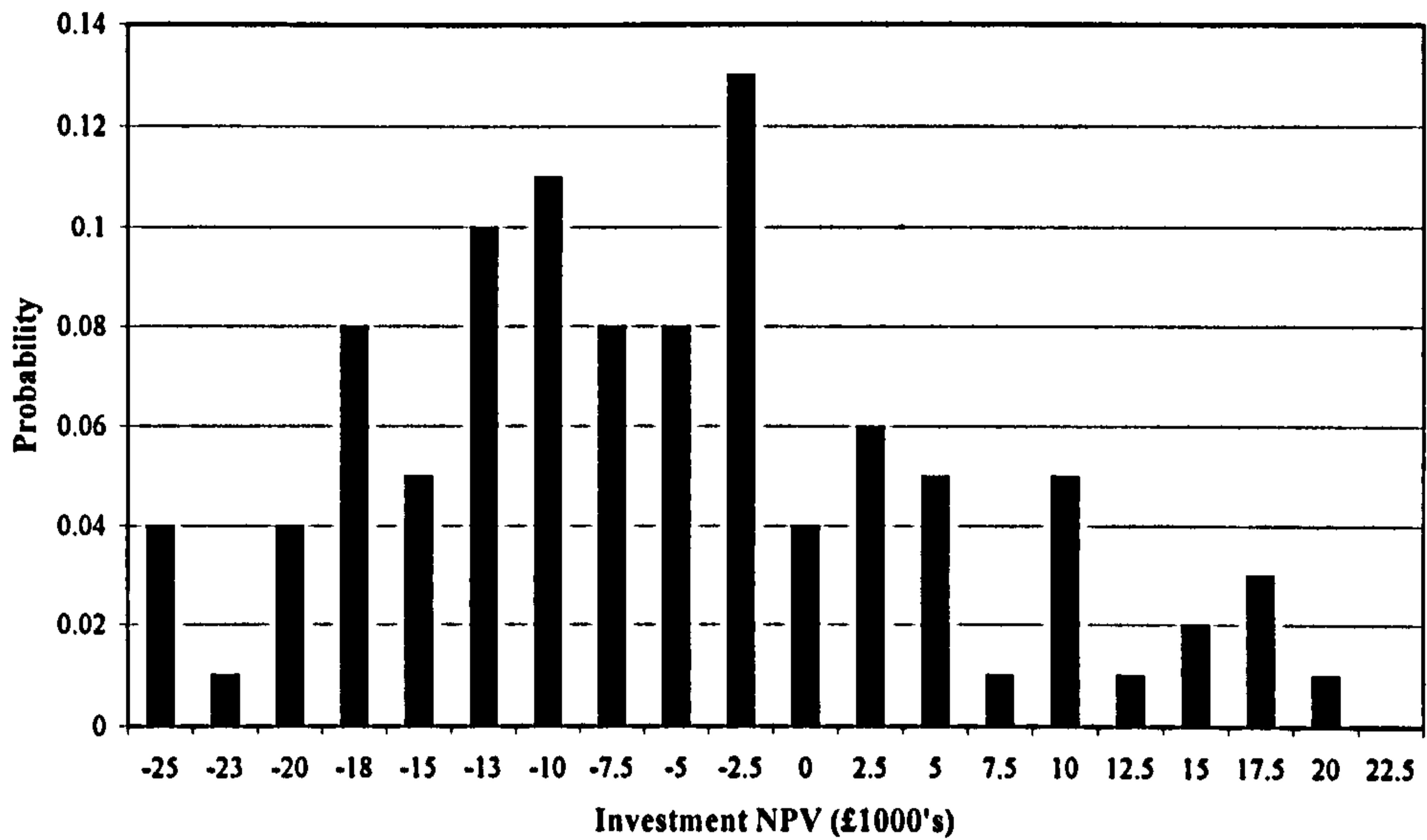


Figure 5.27: Probability distribution of NPV for 100 iterations (normal)

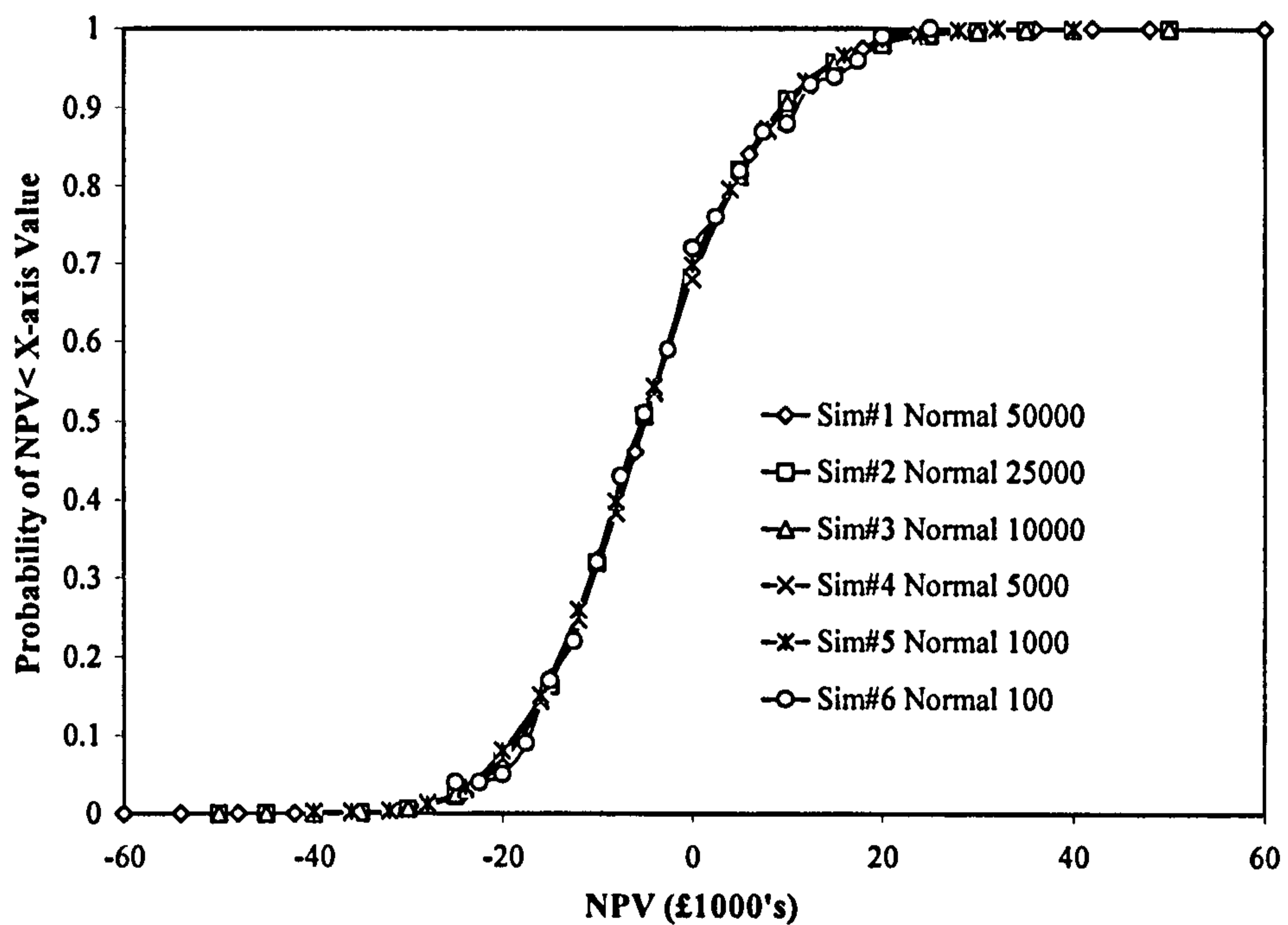


Figure 5.28: The effect of varying the number of iterations (normal)

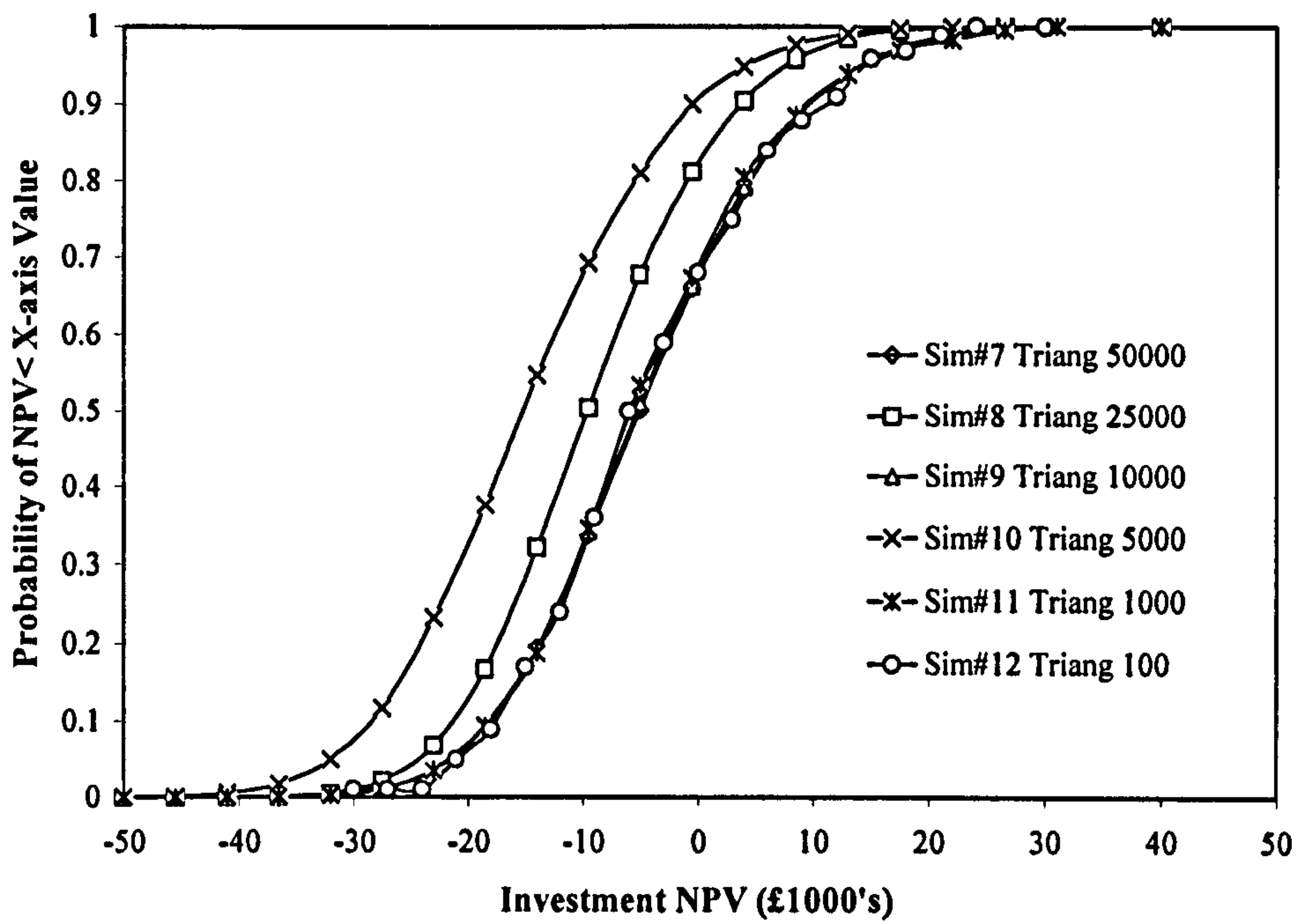


Figure 5.29: The effect of varying the number of iterations (triangular)

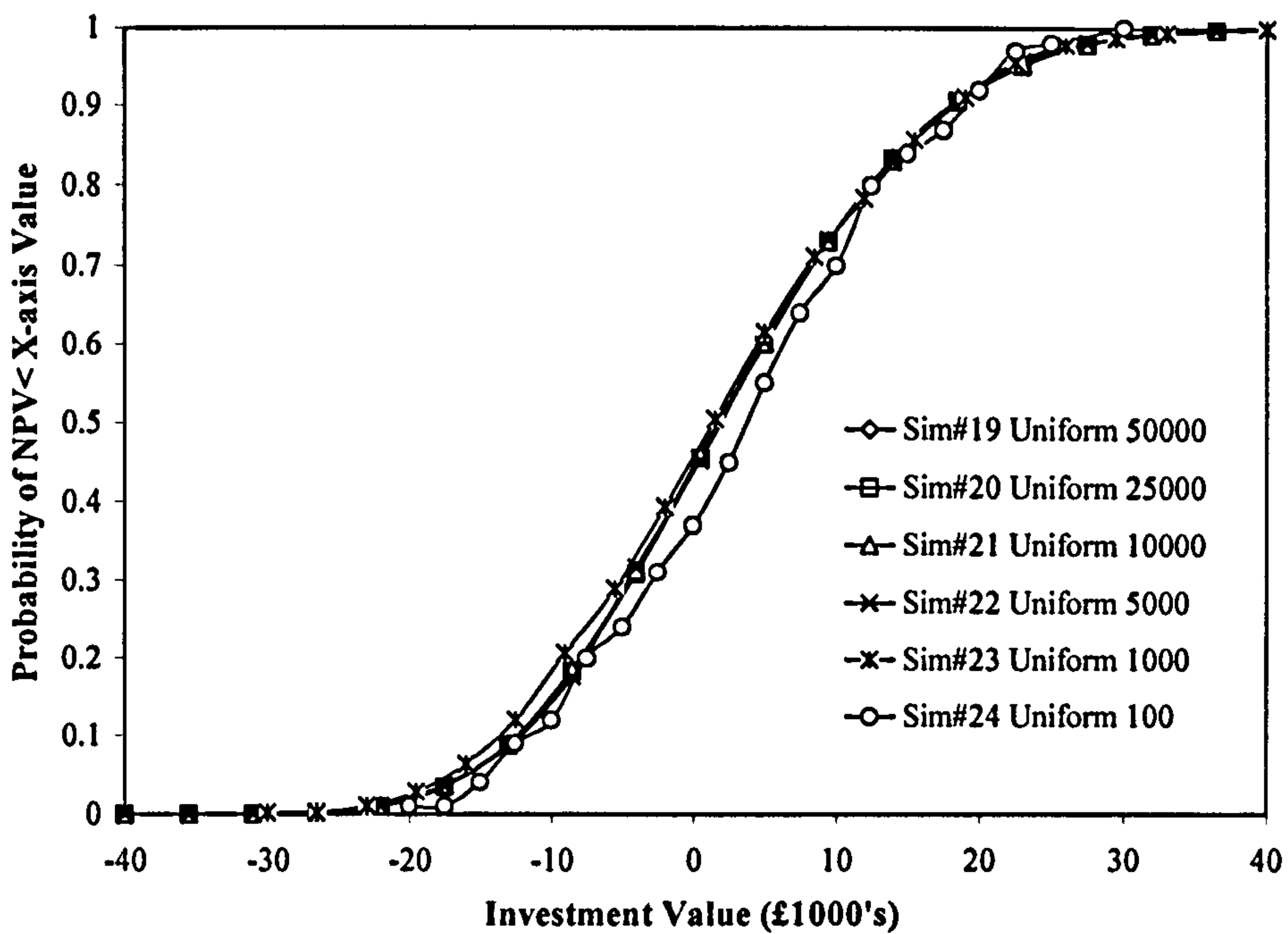


Figure 5.30: The effect of altering the number of iterations (uniform)

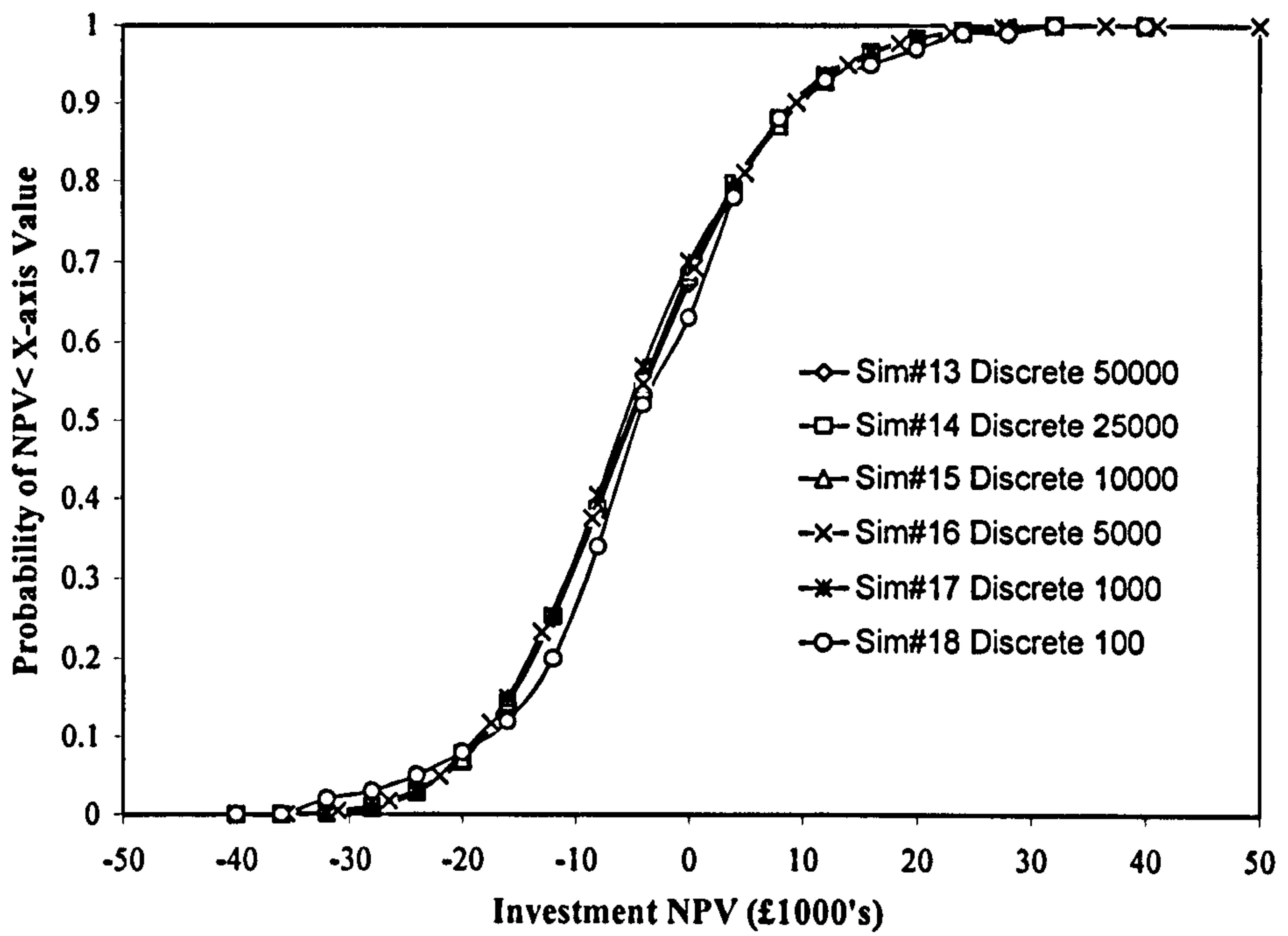


Figure 5.31: The effect of altering the number of iterations (discrete)

Cost component description	Symbol	Unit
Ownership costs	OP	£/year
Operating costs	OW	£/year
Annual cost of repairs and maintenance	R_m	£/year
Hire revenue	HR	£/hour
Total intra-site and inter-site transfer costs	T	£/year
Initial purchase price of machine	P	£
Uniform end-of-series payments	A	£/year
Economic/functional life of machine	n	years
Number of intra-site work stations transfers per year	n_{stin}	No.
Investment time period	t	years
Percentage depreciation per annum	d	%
Depreciation value (t=1,2,3,4,5)	D_t	£/year
Input variable description	Symbol	Unit
Residual/scrap value of machine	S_r	£
Number of inter-site transfers per annum	n_t	No.
Cost of inter-site transfers	C_t	£/transfer
Number of sites per annum	n_s	No.
Work station transfer time period	H_{stm}	Minutes/station
Site set-up costs	S_s	£/per site
Rate of interest (cost of capital)	i	%
Consumable resources per annum	F	£/year
Annual cost of insurance premium	I	£/year
Annual cost of operating licenses	l	£/year
Scheduled maintenance cost as a % of P	ϕ	%
Exponential growth factor of scheduled maintenance	θ_m	No.
Routine maintenance time period	M_t	Minutes/day
Annual hours utilised	H_{yr}	Hours/year
Hours utilised per average working day	H_{day}	Hours/day
Operators hourly rate of pay	L_{op}	£/hour

Table 5.1: Acquisition model cost components and input variables

Company	β	R^2	$r_{SM}=\sqrt{R^2}$	σ_T	$r_{SM}\sigma_T$	$(1-r_{SM})\sigma_T$	E_r
A	1.003	0.124	0.352	25.004	8.808	15.195	14.57
B	0.204	0.002	0.047	38.228	1.793	35.435	7.36
C	0.855	0.118	0.343	37.705	12.947	24.758	13.32
D	1.182	0.426	0.652	16.778	10.944	5.834	16.31
E	1.982	0.189	0.434	45.879	19.919	25.960	23.63
F	-0.250	0.015	0.121	24.512	2.972	21.540	3.22
G	0.767	0.041	0.201	34.848	7.022	27.826	12.52
H	0.899	0.196	0.443	17.839	7.896	9.944	13.72
I	0.528	0.023	0.151	30.774	4.647	26.127	10.33
J	1.019	0.203	0.450	20.739	9.333	11.407	14.83
Σ	8.19					Σ	129.92
μ	0.82					μ	12.99
σ	0.59					σ	5.43

Table 5.2: Summary of contracting sector market model data, 1995 to 2000

Source: Market Eye historical equity data, September 2000

Project Type	Required Return (%)
Replacement	12
Cost saving/application of AMT	15
'Scale' projects, i.e. expansion of existing activities	18
New product development	20
Conceptually new products, i.e. no existing competitors	25

Table 5.3: Subjective risk categories and required rates of return

Source: Pike & Neale 1999

Year	Net Revenue	Corporate Taxation	Tax relief on WDA	Net Cash Flow	Discount Factor	NPV
0	-£100,000.00	£0.00	£0.00	-£100,000.00	1.0000	-£100,000.00
1	£25,513.19	£0.00	£7,500.00	£33,013.19	0.9091	£30,011.99
2	£37,523.14	£7,653.96	£5,625.00	£35,494.19	0.8264	£29,334.04
3	£44,227.02	£11,256.94	£4,218.75	£37,188.82	0.7513	£27,940.51
4	£47,464.40	£13,268.10	£3,164.06	£37,360.36	0.6830	£25,517.63
5	£58,347.34	£14,239.32	£6,492.19	£50,600.20	0.6209	£31,418.75
						£44,222.92

Table 5.4: Calculation of annual net discounted cash flows
Source: adapted from Pike & Neale (1999)

End of Accounting Year	Tax Written Down	Writing Down Allowance	30 % Tax Relief
Initial Outlay	£100,000.00	-	-
[1] WDA @ 25 %	£25,000.00 £75,000.00	£25,000.00	£7,500.00
[2] WDA @ 25%	£18,750.00 £56,250.00	£18,750.00	£5,625.00
[3] WDA @ 25%	£14,062.50 £42,187.50	£14,062.50	£4,218.75
[4] WDA @ 25%	£10,546.88 £31,640.63	£10,546.88	£3,164.06
[5] Sales Proceeds	£10,000.00	-	-
Balancing Allowance	£21,640.63	£21,640.63	£6,492.19
		£90,000.00	£27,000.00

Table 5.5: Calculation of capital allowances and tax relief
Source: adapted from Pike & Neale (1999)

Cost component description	Symbol	Base value
Initial purchase price of machine	P	£100,000.00
Uniform end-of-series payments	A	£23,741.77
Economic/functional life of machine	n	5
Number of intra-site work stations transfers per year	n_{stm}	10
Investment time period	t	0,1,2,3,4,5
Percentage depreciation per annum	d	0.3590 (36.9%)
Depreciation value (t=1,2,3,4,5)	D_t	£36,904.27
Input variable description	Symbol	Base value
Residual/scrap value of machine	S	£10,000.00
Number of inter-site transfers per annum	n_t	7
Cost of inter-site transfers	C_t	£500.00
Number of sites per annum	n_s	5
Work station transfer time period	H_{stm}	30 mins
Site set-up costs	S_s	£1,000.00
Rate of interest (cost of capital)	i	10%
Consumable resources per annum	F	£250.00
Annual cost of insurance premium	I	£500.00
Annual cost of operating licenses	l	£250.00
Scheduled maintenance cost as a % of P	ϕ	10%
Exponential scheduled maintenance growth factor	θ	0.15
Routine maintenance time period	M_t	30 mins
Annual hours utilised	H_{yr}	2500 hrs
Hours utilised per average working day	H_{day}	8 hrs
Operators hourly rate of pay	L_{op}	£9.58 per hr

Table 5.6: Numerical example base parameters

Risk profile property	Mean total cost of site transfers				
	500	550	600	650	700
Minimum	-50936.87	-48514.45	-44150.93	-45300.11	-41989.74
Maximum	55107.07	52395.52	49565.55	55837.79	54368.51
Mean	-4557.36	-3623.55	-2762.18	-1982.48	-939.64
S.D.	10783.23	10828.72	10983.06	11023.84	11162.17
Skewness	0.2677	0.2533	0.2598	0.2769	0.2705
Kurtosis	3.3231	3.2463	3.1908	3.3037	3.3090
Probability of NPV ≤ 0	68.09	64.94	61.76	58.93	55.34

Table 5.7: The effect of varying the mean cost of inter-site transfers (C_t)

Risk profile property	Mean cost of operating licenses				
	250	300	350	400	450
Minimum	-50936.87	-48247.79	-48634.33	-47155.06	-49437.86
Maximum	55107.07	51151.95	64591.07	64520.49	59105.30
Mean	-4557.36	-4649.35	-4576.01	-4566.94	-4498.88
S.D.	10783.23	10827.88	10876.13	10837.67	10852.88
Skewness	0.2677	0.2751	0.2997	0.2702	0.2770
Kurtosis	3.3231	3.2797	3.3614	3.2561	3.3047
Probability of NPV ≤ 0	68.09	68.14	68.09	67.70	67.53

Table 5.8: The effect of varying the cost of operating licenses (I)

Risk profile property	Mean cost of annual insurance premium				
	500	550	600	650	700
Minimum	-50936.87	-45274.56	-44547.52	-50085.83	-45557.03
Maximum	55107.07	47042.20	64485.42	47100.85	53526.77
Mean	-4557.36	-4557.49	-4540.03	-4521.19	-4504.52
S.D.	10783.23	10804.84	10815.81	10861.89	10851.78
Skewness	0.2677	0.2701	0.2797	0.2644	0.2584
Kurtosis	3.3231	3.2374	3.2988	3.2955	3.2651
Probability of NPV ≤ 0	68.09	68.08	67.79	67.68	67.74

Table 5.9: The effect of varying the cost of annual insurance premium (I)

Risk profile property	Mean hours utilised per annum		
	2000	2250	2500
Minimum	-50936.87	-46337.73	-45846.71
Maximum	55107.07	57465.41	46212.15
Mean	-4557.36	-3837.79	-3149.29
S.D.	10783.23	10846.35	10913.54
Skewness	0.2677	0.2611	0.2570
Kurtosis	3.3231	3.2748	3.2678
Probability of NPV ≤ 0	68.09	65.62	63.12

Table 5.10: The effect of varying the total hours utilised per annum (H_{yr})

Risk profile property	Operators hourly rate of pay				
	Class 2 £8.65	Class 1 £9.58	£10.00	£12.50	£15.00
Minimum	-61357.72	-50723.80	-45405.91	-47517.66	-42630.79
Maximum	58370.86	53043.72	56830.71	51729.18	58734.60
Mean	-4874.31	-4302.52	-4053.67	-2436.98	-874.69
S.D.	10806.04	10864.90	10900.00	10953.24	11148.83
Skewness	0.2645	0.2671	0.2576	0.2679	0.2787
Kurtosis	3.2496	3.2833	3.2830	3.2460	3.2770
Probability of NPV ≤ 0	68.94	66.97	66.02	60.61	55.11

Table 5.11: The effect of varying operators hourly rate of pay (L_{op})

Risk profile property	Mean hours utilised per day				
	6	7	8	9	10
Minimum	-45088.98	-45724.07	-50936.87	-54663.04	-44200.31
Maximum	54419.88	54978.59	55107.07	51931.30	54256.49
Mean	-4524.40	-4518.82	-4557.36	-4596.47	-4667.61
S.D.	10866.01	10830.92	10783.23	10854.54	10829.20
Skewness	0.2680	0.2659	0.2677	0.2696	0.2893
Kurtosis	3.2905	3.2584	3.3231	3.3239	3.2812
Probability of NPV ≤ 0	67.68	67.74	68.09	68.11	68.33

Table 5.12: The effect of varying the average hours utilised per day (H_{day})

Risk profile property	Mean daily routine maintenance period			
	30	40	50	60
Minimum	-50936.87	-49607.84	-49594.50	-53567.43
Maximum	55107.07	50147.89	54421.90	54632.09
Mean	-4557.36	-4471.84	-4425.88	-4248.32
S.D.	10783.23	10890.88	10865.08	10827.12
Skewness	0.2677	0.2690	0.2567	0.2637
Kurtosis	3.3231	3.2657	3.2665	3.2519
Probability of NPV ≤ 0	68.09	67.71	67.33	66.75

Table 5.13: The effect of varying the daily routine maintenance period (M_t)

Risk profile property	Mean work stations per site				
	12	14	16	18	20
Minimum	-45849.84	-55909.36	-44616.62	-47792.14	-45587.36
Maximum	56031.50	50549.43	54349.38	47239.60	53042.91
Mean	-4464.59	-4470.56	-4507.67	-4489.15	-4480.67
S.D.	10658.03	10613.00	10659.75	10650.48	10587.32
Skewness	0.2437	0.2303	0.2862	0.2382	0.2416
Kurtosis	3.3190	3.2399	3.3870	3.2316	3.2315
Probability of NPV ≤ 0	67.65	67.65	68.14	67.90	67.75

Table 5.14: The effect of varying the number of work stations per project (n_{stm})

Risk profile property	Mean work station transfer period		
	40	50	60
Minimum	-46457.06	-53390.25	-50103.29
Maximum	49422.67	46334.43	52764.77
Mean	-4648.57	-4533.53	-4610.33
S.D.	10681.09	10622.86	10622.69
Skewness	0.2749	0.2698	0.2562
Kurtosis	3.3932	3.1860	3.3597
Probability of NPV ≤ 0	68.54	68.04	68.42

Table 5.15: The effect of varying the work station transfer period (H_{stm})

Risk profile property	Mean cost of capital			
	12.5%	15%	20%	25%
Minimum	-47999.05	-52938.43	-54320.14	-57716.56
Maximum	42902.92	28406.53	8382.03	1425.01
Mean	-9199.25	-14733.23	-24035.87	-31718.72
S.D.	9688.61	8917.46	7513.68	6424.85
Skewness	0.2615	0.2499	0.2317	0.2513
Kurtosis	3.3409	3.2151	3.2443	3.3095
Probability of NPV ≤ 0	83.51	94.38	99.75	99.99

Table 5.16: The effect of varying the cost of capital (i)

Risk profile property	Mean residual value				
	11000	12000	13000	14000	15000
Minimum	-50256.16	-49563.30	-56323.84	-53041.13	-57972.95
Maximum	43820.96	41834.64	35121.64	27491.47	27586.44
Mean	-7334.04	-9780.94	-12040.32	-14128.04	-15936.67
S.D.	10267.80	9852.24	9584.90	9432.92	9211.03
Skewness	0.2459	0.2610	0.1845	0.1622	0.1510
Kurtosis	3.2923	3.3961	3.2695	3.2030	3.2534
Probability of NPV ≤ 0	77.33	84.44	89.42	92.97	95.42

Table 5.17: The effect of varying the residual machine value (S_r)

Risk profile property	Mean scheduled maintenance costs			
	0.125	0.15	0.175	0.20
Minimum	-46118.18	-50936.87	-55227.21	-53977.39
Maximum	46518.06	55107.07	46166.54	46485.62
Mean	-2592.36	-4557.36	-6608.96	-8568.82
S.D.	10465.25	10783.23	10931.54	11258.16
Skewness	0.2844	0.2677	0.2293	0.1938
Kurtosis	3.2521	3.3231	3.2913	3.2810
Probability of NPV ≤ 0	61.60	68.09	74.11	78.62

Table 5.18: The effect of varying the scheduled maintenance costs (ϕ)

Risk profile property	Mean exponential growth rate			
	0.10	0.15	0.20	0.25
Minimum	-31043.48	-50936.87	-48045.73	-66279.84
Maximum	62707.31	55107.07	48661.91	44863.20
Mean	3673.62	-4557.36	-5378.28	-11488.07
S.D.	10165.48	10783.23	10832.05	11770.30
Skewness	0.4151	0.2677	0.2511	0.1199
Kurtosis	3.4418	3.3231	3.3102	3.3104
Probability of NPV ≤ 0	37.89	68.09	70.62	83.84

Table 5.19: The effect of varying the growth scheduled maintenance costs (θ)

Risk profile property	Input distribution type (50000 iterations)			
	Normal	Triangular	Discrete	Uniform
Minimum	-50936.87	-43305.81	-37770.04	-35618.48
Maximum	55107.07	38307.69	33292.90	45816.26
Mean	-4557.36	-4569.25	-4520.62	2353.36
S.D.	10783.23	10767.77	10770.46	11671.42
Skewness	0.2677	0.2095	0.2223	0.2201
Kurtosis	3.3231	2.9395	2.9670	2.8005
Probability of NPV ≤ 0	68.09	67.49	67.29	43.90

Table 5.20: NPV risk profile statistical properties with varied input distributions

Risk profile property	Number of iterations					
	50000	25000	10000	5000	1000	100
Minimum	-50936.87	-48531.63	-41828.79	-39539.47	-38470.05	-24321.37
Maximum	55107.07	48170.52	45008.67	36347.34	31789.70	20193.70
Mean	-4557.36	-4634.16	-4640.01	-4554.57	-4842.72	-4586.54
S.D.	10783.23	10793.94	11027.73	10851.67	10902.51	10505.42
Skewness	0.2677	0.3140	0.2779	0.2178	0.1826	0.3677
Kurtosis	3.3231	3.4075	3.2743	3.1666	3.0138	2.5749
Probability of NPV ≤ 0	68.09	68.27	68.02	67.92	69.80	72.70

Table 5.21: NPV risk profile statistical properties with varied iterations (normal)

Risk profile property	Number of iterations					
	50000	25000	10000	5000	1000	100
Minimum	-43305.81	-40940.13	-43665.11	-39967.94	-27822.35	-27010.16
Maximum	38307.69	40852.26	35014.28	40377.98	23614.14	17700.64
Mean	-4569.25	-4606.31	-4703.90	-4724.80	-4478.18	-5267.04
S.D.	10767.77	10764.84	10746.54	10954.17	10657.09	10517.67
Skewness	0.2095	0.2229	0.2124	0.2091	0.3569	-0.0073
Kurtosis	2.9395	2.9600	2.9531	2.9703	2.6814	2.5935
Probability of NPV ≤ 0	67.49	67.76	67.75	67.83	68.77	69.71

Table 5.22: NPV risk profile statistical properties with varied iterations (triangular)

Risk profile property	Number of iterations					
	50000	25000	10000	5000	1000	100
Minimum	-37770.04	-38274.89	-38166.37	-36838.95	-34677.45	-34570.36
Maximum	33292.90	34182.40	34721.61	32077.12	30897.97	25059.63
Mean	-4520.62	-4638.66	-4659.33	-4339.42	-4953.79	-4139.73
S.D.	10770.46	10695.80	10818.31	10787.89	10739.99	11779.27
Skewness	0.2223	0.2108	0.2442	0.1969	0.3064	0.2092
Kurtosis	2.9670	2.9863	2.9716	2.9906	3.0849	3.1432
Probability of NPV ≤ 0	67.29	67.89	68.69	67	70	66.60

Table 5.23: NPV risk profile statistical properties with varied iterations (discrete)

Risk profile property	Number of iterations					
	50000	25000	10000	5000	1000	100
Minimum	-35618.48	-34813.71	-35085.91	-31661.92	-27413.58	-18502.43
Maximum	45816.26	49794.20	44340.17	46871.38	38973.67	27172.70
Mean	2353.36	2431.51	2325.57	2378.00	1766.36	3508.27
S.D.	11671.42	11692.62	11714.74	11668.42	11996.68	11004.00
Skewness	0.2201	0.2321	0.2086	0.2079	0.1828	0.0029
Kurtosis	2.8005	2.8072	2.8003	2.7708	2.6255	2.2553
Probability of NPV ≤ 0	43.90	43.84	44.19	43.85	46.75	37.08

Table 5.24: NPV risk profile statistical properties with varied iterations (uniform)

Input Variable	Sensitivity (R²=0.9717)
<i>i</i>	-0.6452
<i>S_s</i>	-0.4763
<i>θ</i>	-0.4477
<i>φ</i>	-0.2620
<i>H_{yr}</i>	0.0933
<i>n_s</i>	0.0387
<i>n_t</i>	0.0283
<i>L_{op}</i>	0.0273
<i>S</i>	0.0245
<i>C_t</i>	0.0204
<i>M_t</i>	0.0108
<i>H_{day}</i>	-0.0063
<i>I</i>	0.0045
<i>F</i>	0.0023
<i>l</i>	0.0020
<i>H_{stn}</i>	0.0020

Table 5.25: Investment NPV sensitivity analysis ($\rho = 0.80$)

Input Variable	Sensitivity (R²=0.9710)
<i>i</i>	-0.6569
<i>S_s</i>	-0.4776
<i>θ</i>	-0.4506
<i>φ</i>	-0.2650
<i>C_t</i>	0.1758
<i>H_{yr}</i>	0.0943
<i>n_s</i>	0.0380
<i>n_t</i>	0.0290
<i>L_{op}</i>	0.0271
<i>S</i>	0.0245
<i>M_t</i>	0.0115
<i>H_{day}</i>	-0.0057
<i>I</i>	0.0042
<i>F</i>	0.0026
<i>l</i>	0.0026
<i>H_{stn}</i>	0.0000

Table 5.26: Investment NPV sensitivity analysis ($\rho = 0$)

Risk profile property	Input distribution type (50000 iterations)			
	Normal	Triangular	Discrete	Uniform
Skewness	0.2677	0.2095	0.2223	0.2201
Kurtosis	3.3231	2.9395	2.9670	2.8005
Bowman-Shelton value	0.325872	0.149351	0.165632	0.194647

Table 5.27: Bowman-Shelton output normality test statistics

Sample size (n)	10% point	5% point
20	2.13	3.26
30	2.49	3.71
40	2.70	3.99
50	2.90	4.26
75	3.09	4.27
100	3.14	4.29
125	3.31	4.34
150	3.43	4.39
200	3.48	4.43
250	3.54	4.51
300	3.68	4.60
400	3.76	4.74
500	3.91	4.82
800	4.32	5.46
∞	4.61	5.99

Table 5.28: Significance points of the Bowman-Shelton statistic

Source: Newbold 1991

CHAPTER 6

REAL OPTION ANALYSIS OF STRATEGIC CONSTRUCTION AUTOMATION INVESTMENT

6.1 Introduction

Real option valuation complements NPV analysis as the principle tool for understanding the value of the firm. The firm's ability to influence environmental conditions in favour of their strategic options is the essence of the real option-pricing perspective in strategic management (Anderson 2000). In an uncertain environment, having the flexibility to decide what to do after uncertainty is resolved has value (Merton 1998). Real options indicate that the investment decisions of firms are better understood by using an option framework rather than the more conventional present-value analysis framework (Scholes 1998).

Oil, gas, gold, coal, and copper production companies have implemented real option pricing to value their operations and continue to be some of the largest users (Coy 1999). Table 6.1 introduces the application of real options encountered within the construction industry and the authors who have presented analysis of these investment options.

The application of real option-pricing theory to the valuation of construction mechatronics is described in this chapter. Learning, abandonment and switching option scenarios are described within the context of construction automation valuation. Furthermore, investment timing (deferral) and strategic growth options are outlined with worked examples. The study provides insight into the strategic value of construction automation

investment opportunities and assesses the application of real option-pricing theory in the valuation of such opportunities. Through the application of real option-pricing theory to construction automation investment, technology strategists can more effectively assess crucial opportunities to delay, deploy or abandon capital intensive investments as events unfold and as technological and operational uncertainties are resolved. The following sections describe the limitations of DCF valuation methodologies, introduces the use of real option-pricing for construction automation investment valuation, the basic theory of financial options and their analogy to strategic investment options.

6.2 Limitations of DCF valuation methodologies

Traditional DCF investment appraisal techniques alone, systematically undervalue strategic investment opportunities (Kemna 1993; Smith & Nau 1995; Busby & Pitts 1998; Smith & McCardle 1999; Huchzermeier & Loch 2001; Copeland & Antikarov 2001). Smith and McCardle (1999) comments upon the concern among managers that the use of blanket risk-adjusted discount rates causes them to undervalue projects with long time horizons. NPV analyses assume immutable investment scenarios and do not incorporate the flexibility, which may be available when valuing innovative technology investment. On an NPV basis, the high implementation costs, low estimated future cash flows, and sensitivity to the cyclical nature of the construction sector, may combine to render construction automation investment unattractive. However, more realistically NPV may fluctuate as new information is obtained regarding system prices, operating costs, taxation, government policy, the economy and capital costs (Mann *et al* 1992). Solitary DCF investment appraisal methodologies do not capture and reward the value of managerial flexibility (Busby & Pitts 1997; Coy 1999). Traditional DCF methodologies fail to provide an

adequate decision making framework because they do not value management's ability to wait, to revise the initial operating strategy if events turn out to be different from expected and to account for future (dis)investment (Lander & Pinches 1998). Furthermore, it has been suggested that real option valuation denigrate NPV appraisal alone, as the principle tool for understanding the value of a firm (Kogut & Kulatilaka 2001).

Real options indicate that the investment decisions of firms are better understood by using an option framework rather than the more conventional present-value analysis framework (Scholes 1998). Real options are created through moderating losses or exploiting new capital investment opportunities. Within an uncertain business environment, having the flexibility to decide what to do after uncertainty is resolved has value (Merton 1998). NPV analyses assume that management is passive in their attitude towards investment projects and that future project value remains static in response to unexpected developments (Luehrman 1998; Trigeorgis 1996, 1993). Corporate management may play an active role in achieving or exceeding the original estimated NPV of a project. The firm's ability to influence environmental conditions in favour of their strategic options is the essence of the real option-pricing perspective in strategic management (Anderson 2000).

6.3 Strategic construction automation valuation: a real option-pricing approach

Strategy may be defined as a rational set of time-sequenced actions aimed at gaining a sustainable advantage over competition and improving market position. Strategy is a vision describing what the organisation should be in the future. Specifically, Porter (1985) defined technology strategy as a firm's approach to the development and use of technology. The choices guided by strategy relate to the range of the organisation's products or services,

market, principle capabilities, growth rate, return from and allocation of resources. A strategic plan is a detailed and specific declaration of the organisation's intentions with regards to its clients, competitors, suppliers, investors, equipment, employees and the future of the firm. Finally, strategic planning requires commitment of resources, both financial and personnel, for its implementation.

Developing a strategy for a business undergoing revolutionary technological change is a daunting proposition (Porter 1996). Strategic investment entails high risk when expected revenue streams are uncertain and potentially volatile. Investment must often be undertaken on the basis of potential significant returns or through the need to remain competitive within an industrial sector (Mann *et al* 1992). Trigeorgis (1996) described the strategic NPV of an investment opportunity as a function of the standard NPV plus an investment flexibility component. The flexibility component incorporates the value of operating and strategic options from active management of the potential investment opportunities.

This may be summarised as:

$$\begin{aligned} \text{Expanded (strategic) NPV} &= \text{static (passive) NPV of expected cash flows} \\ &+ \text{value of real option from active management} \end{aligned}$$

Alternatively, according to Busby and Pitts (1998) the value of any capital investment may be separated in two component parts:

1. the value of the investment if management had no flexibility of action, and

2. the value of managerial flexibility.

The mapping of a construction automation investment as a pioneer venture typically relates to an investment with a high initial expenditure and low prospective cash flows. The decision tree presented in Figure 6.1 summarises a selection of the real options available when considering construction automation investment.

Automated construction technology exposes investors to risks previously not encountered with the purchase of traditional construction plant and machinery. Furthermore, it is difficult to accurately estimate future cash flows for feasibility studies regarding the implementation of prototype or exemplary construction plant and machinery. Historical project data is either unavailable or sensitive to the operations of the implementing organisation. Emerging technologies may provide opportunities for profitability and growth within the UK construction sector. Prudent investment may permit an organisation to prove automated construction technology, gain a positive track record and enhance their ability to utilise imminent construction automation technology. Real option valuation may assist in the positive appraisal, selection and implementation of innovative construction mechatronics technology.

6.4 Basic theory of financial options

In financial markets, options are contractual arrangements giving the owner the right, but not the obligation, to buy (call) or sell (put) an equity or commodity at a given price at some distant point in the future. In return for the option, the purchaser pays a fee premium. The

cost of the option depends upon the volatility of the underlying equity and the exercise price.

There are two parties to an option contract; the buyer and the seller. The buyer has the right, but not the obligation, to exercise the option, whilst the seller receives the premium. One feature of an option is that, if the share price does not move as expected the option becomes worthless and the buyer has only lost the premium originally paid. The dynamic relationship between the value of a traded option, its time to expiration and the value of the underlying equity was captured within a partial differential equation developed by Black and Scholes (1973). The Black and Scholes model prices an option using five variables: share price (of underlying equity), option exercise price, risk-free rate of interest, share price volatility and time. The option is only exercised if it is profitable. Therefore, if the option is not exercised, the initial premium paid is lost.

6.4.1 Call option

A call option gives the owner the right, but not the obligation, to purchase the underlying equity subject to the conditions of the option contract. The conditions of the contract may specify the exercise price and the time to expiration of the option. It could be profitable to exercise a call option if the market price of the underlying equity is greater than the exercise price. Therefore, the owner of the option contract would be able to purchase the equity at a price lower than the current market value. This would facilitate the owner of the option contract to make a profit by selling the equity at the market price and realising a profit. Figure 6.2 depicts the profit and loss profile for a call option at expiry.

6.4.2 Put option

A put option gives the owner the right, but not the obligation, to sell the underlying equity subject to the conditions of the option contract. It is only profitable to exercise a put option if the underlying equity value remains below the exercise price of the put option contract. If the option is exercised the owner may sell the underlying equity at a price greater than the market value. Figure 6.3 depicts the profit and loss profile for a put option at expiry.

6.4.3 European and American options

European style options, whether call or put contracts, can only be exercised on the maturity (expiration) date of the option contract. American style option contracts, whether call or put options, can be exercised at any time up to and including the maturity date of the option contract. The distinction between European and American options is not associated with the geographical location of the option exchange or the writer of the option contract. Both classifications of call and put option contract are traded throughout international stock exchanges.

6.4.4 The option premium

The option premium can be subdivided into its two components: intrinsic value and time value. The intrinsic value of the option is equal to the underlying price of the option minus the exercise value. The minimum intrinsic value is equal to zero. It would be irrational to sell an option with a premium lower than the intrinsic value of the option, since more could be obtained from exercising it. There would be a certain profit from purchasing the option, instantly exercising it and selling the acquired equity. The time value of an option is based

upon the volatility of the underlying equity, the time to expiration and the extent to which the option is in or out-of-the-money.

If an option is said to be in-the-money, immediate exercise would have positive value. A call option contract would be '*in-the-money*' if the current price of the underlying was greater than the exercise price of the option, i.e. $S > X$. A put option contract is in-the-money if the current underlying price is less than the exercise price, i.e. $S < X$.

An option is '*out-of-the-money*' when immediate exercise would not be profitable. For example a call option contract would be out-of-the-money if the price of the underlying asset was less than the strike price, i.e. $S < X$. A Put option would be out-of-the-money if the current price of the underlying was greater than the exercise price, i.e. $S > X$. Out-of-the-money option contracts have lower time value than at-the-money options since the stock price has further to move before intrinsic value is attained.

Finally, an option is '*at-the-money*' if the exercise price and the current price of the underlying are equal. At-the-money options have no intrinsic value. In-the-money option contracts have lower time value than at-the-money contracts since their premium contains intrinsic value, which is vulnerable to a drop in the value of the underlying asset.

6.4.5 Intrinsic and time value

At the expiry date, an option premium will be equal to the intrinsic value of the option. Preceding maturity, the option premium would surpass the intrinsic value. The static NPV of a real option is the intrinsic value. The excess of the premium paid over the intrinsic value of the option is known as the *time value*. The total value of an option can be defined

as the maximum of zero and the value it would have if it were exercised immediately. For a call option, the intrinsic value is, therefore, $\text{Max}(S - X, 0)$. For a put option, it is $\text{Max}(X - S, 0)$. The total value of an option can be thought of as the sum of its intrinsic value and its time value (Hull 2000). Below the exercise price, the price of the option consists of time value only, but above the exercise price the price consists of both intrinsic and time value.

6.5 Solution techniques

The following sub-sections outline the various mathematical techniques, which may be used to value financial options. Initially, the Black and Scholes technique is presented following with the Binomial model. Subsequently, these techniques may be used in the valuation of real assets by applying real option-valuation theory.

6.5.1 The Black and Scholes model

The quantitative origins of real options are derived from the seminal work of Black and Scholes (1973) in the pricing of financial options. The Black and Scholes option valuation model has become the standard model for valuing financial options. The B&S model was developed for the valuation of financial derivatives, therefore, it has underlying assumptions that more naturally apply to options traded in financial securities (Benaroch & Kauffman 1999). In this section, the generalised B&S formulae are presented. The derivation of the B&S formula may be obtained from standard textbooks.

The B&S model is a continuous-time model and assumed that the value of the underlying is log-normally distributed, or that returns are normally distributed. Changes in the value of the underlying asset are modelled as geometric Brownian motion (GBM), where μ is the

known and constant expected rate of return, σ is the known and constant volatility and a standard Wiener process (dz) represents uncertainty:

$$dV = \mu V dt + \sigma V dz \quad 6.1$$

Assuming that no dividends are payable on the stock prior to maturity of the option, the Black and Scholes formula for the price of a European call option at time zero, C , is given by the following closed form solution:

$$C = S_0 N(d_1) - X e^{-rt} N(d_2) \quad 6.2$$

where

$$d_1 = \frac{\ln\left(\frac{S_0}{X}\right) + \left(r + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} \quad 6.3$$

$$d_2 = \frac{\ln\left(\frac{S_0}{X}\right) + \left(r - \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} = d_1 - \sigma\sqrt{t} \quad 6.4$$

and $N(x)$ is the cumulative probability distribution function for a variable that is normally distributed with a mean of zero and a standard deviation of 1.0 (i.e., it is the probability that such a variable will be less than x). S_0 is the stock price at time zero, X is the strike price, r is the continuously compounded risk-free rate of return, σ is the stock price volatility, and T is the time to maturity of the option.

The expression e^{-rt} is a discount term similar to $1/(1+r)^t$ and is such that it determines the present value of the future capital expenditure (option exercise price) at the time to expiration, t . The distinct feature of e^{-rt} is that it discounts on a continuous basis (Redhead 1997). The frequency of compounding affects the value of the outcome. The effective interest rate increases as the frequency of compounding rises. Continuous compounding is based upon an infinite number of infinitely small (usually daily) periods. The effect of discounting also depends upon the time period, i.e. annual discounting or discounting continuously over a year will provide different results (continuous discounting over a year will yield a smaller discount term).

The parameters $N(d_1)$ and $N(d_2)$ are based upon a standardised normal distribution, which is a normal distribution whose horizontal axis is in the units of the stock price volatility. These terms take into account the risk of the option being exercised. $N(d_1)$ reflects the cumulative probability related to the current value of the underlying; its value shows the amount by which the option premium increases for each unit increase in the underlying. The value of $N(d_1)$ lies between 0 and 1. If a financial security is deeply out-of-the-money, any rise in the value of the underlying will have little effect upon the value of the call, since it remains unlikely that the option will be exercised ($N(d_1)$ will be close to zero). If the call option is currently at-the-money, there will be a 50% probability that it will end up in-the-money and a 50% probability that it will be out-of-the-money ($N(d_1) = 0.5$). Therefore, if the underlying increases by one unit, the value of the call will increase by 0.5 units. If the option is already deep in-the-money, each unit increase in the value of the underlying stock will be reflected in the value of the call ($N(d_1) = 1.0$). The greater the security price in relation the exercise price, the greater the value of $N(d_1)$.

$N(d_2)$ reflects the probability that the call option will actually be exercised. If $N(d_2) = 0.7$, there will be a 70% chance that the call option will be profitably exercised. Only if the option is certain to be exercised will $N(d_1) = N(d_2) = 1.0$ (Redhead 1997).

The term S_0/X is the natural logarithm of the price relative (ratio of stock price to exercise). The model uses a log-normal rather than normal distribution. The reason for using the log-normal distribution is that the price relative may never be negative, hence, the price relative can not be normally distributed. This is due the option being deemed worthless when $S < X$. The natural logarithm of the price relative can be negative and will be normally distributed (the natural logarithm of the price relative is the continuously compounded rate of return on the stock).

The B&S model assumes that investors are risk neutral. This assumption eliminates the need to estimate the opportunity cost of capital for the option (Benaroch & Kauffman 1999). Risk-neutral valuation infers that the risk aversion of the decision analyst does not enter the appraisal methodology. This is dissimilar to traditional investment appraisal techniques, where, the cost of capital reflects the risk reward characteristics of the investment opportunity.

The assumptions of the B&S model include (Hull 2000):

- stock price follows a continuous time stochastic process;
- short selling of securities with full use of proceeds is permitted;
- no transaction costs or taxes and all securities are perfectly divisible;
- no dividends paid during the life of the derivative;
- no risk-less arbitrage opportunities;

- security trading is continuous, and
- the risk-free rate of interest is constant and the same for all securities.

It is essential to understand the assumptions behind the B&S formulae in order to place the resulting real option-valuation into perspective. If the equivalent investment project values can be found for the B&S parameters, the model should provide an approximate value for the option to make a capital investment (Mann *et al* 1992).

6.5.2 Binomial model

The assumption that the underlying asset follows a multiplicative binomial process over discrete time periods underlies the numerical option pricing procedure developed by Cox, Ross and Rubenstein (1979). The binomial model is a simple discrete-time option pricing formula. A detailed derivation of the Binomial model is presented within this section. Binomial models can cope with the possibility of early exercise, and can therefore be used to price American options. Binomial models can also allow for variation in interest rates and volatility over time.

The Binomial model assumes that the future values of the underlying asset follow a multiplicative binomial process. The model assumes that the up and down parameters (u and d) and the volatility of the underlying asset are constant and known from the outset. Furthermore, the technique uses risk-neutral probabilities (p and $1-p$). The life of the option is divided into a large number of small time intervals of length Δt . In each time interval the stock price moves from its initial value of S_0 to one of two new values, S_0u and S_0d .

In general, $u > 1$ and $d < 1$. The probability of an up movement is denoted by p and the probability of a downward movement is denoted by $1-p$. In the next time period, the asset value will be, $S_0 u^2$, $S_0 ud$ or $S_0 d^2$. Figure 6.4 depicts a five step Binomial tree showing asset values at the end of each step.

In practice, the life of an option is divided into 30 or more time steps of length Δt . Using the Binomial model to value automated construction technology infers that Δt is equal to one fiscal year and the binomial tree extends for a number of time periods equal to the economic life of the valued machine.

In each time interval it is assumed that value of the investment cash flows moves from its initial estimated value of S_0 , to one of two new values S_0u or S_0d . At time Δt , there are two possible values of the projects cash flows, S_0u and S_0d . The probability of an upward price movement is p , and the probability of a downward movement is $(1-p)$. At time $2\Delta t$, there are three possible values, S_0u^2 , S_0 , and S_0d^2 . The probability of these movements are p^2 , $2p(1-p)$ and $(1-p)^2$. In general, at time $i\Delta t$, $i+1$ stock prices are considered (Hull 2000). These are:

$$S_0 u^j d^{i-j} \quad j = 0, 1, \dots, i \quad 6.5$$

In each step, there is a binomial stock price movement, which models the NPV of the project cash flows. Hull (2000) outlined equations for calculating jump probabilities and jump amplitudes. These are:

$$p = \frac{a - d}{u - d} \quad 6.6$$

$$u = e^{\sigma\sqrt{\Delta t}} \quad 6.7$$

$$d = e^{-\sigma\sqrt{\Delta t}} \quad 6.8$$

$$a = e^{r\Delta t} \quad 6.9$$

The variable a is often referred to as the *growth factor*.

The Binomial option pricing model assumes risk neutral valuation and represents the behaviour of equity price movements in a risk neutral world, and assumes that:

- the expected return from all traded securities is the risk free rate of interest, and
- future cash flows can be valued by discounting their expected values at the risk free interest rate (return on 3-month Treasury bills).

In theory the binomial diffusion process can be reviewed as an approximation to the actual movements of security prices. The reason lies with the fact that determining the values for u and d is a difficult empirical problem because asset prices rarely follow the classical multiplicative binomial process.

6.6 Real option volatility

Counter intuitively, investments with greater cash flow uncertainty have greater real option value (Amram & Kulatilaka 1999c). Having traditionally based investment appraisal upon accepting only projects with a positive NPV, deriving value from uncertainty regarding the possibility of positive returns is not perceptible. The greater the volatility of investment cash flows, the greater the probability that these cash flows will increase or decrease in

value. The volatility of a real asset is inherently difficult to measure or estimate (Kemna 1993). Warszawski and Navon (1998) commented that within other industrial sectors, automated technology is often justified upon intangible benefits (e.g., improved safety, high quality and dependability) and that within the volatile and cyclical construction industry these may be more difficult to evaluate. However, the volatility of possible tangible and intangible benefits may add to the real option value of construction automation investment opportunities.

Figure 6.5 describes the sources of investment volatility concerning construction automation technologies. The more variable a machine's returns, the greater the value of the option to invest in that technology. The more volatile the price of the underlying, the more valuable the option becomes, as potential returns are greater, although potential losses are limited to the price of the option. According to McGrath (1997), the volatility of new markets (i.e. new automated construction technology) is greater than that of established markets, within which options have greater value. Factors, which may signal how attractive the structure of construction automation industry demand include the following:

- whether construction automation may solve many of few problems;
- whether these problems are widespread throughout the construction industry;
- whether these problems are growing;
- whether these problems recur or are resolved, and
- whether these problems recur frequently.

Volatility is seldom likely to remain constant over the economic life of the systems in question. Volatility may decline over the option life, reflecting a situation within which the

market for the technology contracts further to a period of rapid implementation. The market contraction may be caused by the massive initial adoption of the available systems, followed by a rapid slow down when implementation and operating problems occur. As volatility is reduced, and the expected, but initially uncertain outcome becomes known to the analyst, real option pricing becomes less attractive (Benaroch & Kauffman 1999). Lower uncertainty in future demand conditions may be reflected in lower volatility of the expected investment value (Anderson 2000).

Table 6.2 presents a summary of the various approaches outlined within the existing literature for determining cash flow volatility within real option valuations. These alternative approaches are discussed in the following sections.

6.6.1 Estimated

Based upon the possible sources of construction automation investment volatility described in Figure 6.5, investment analysts may provide subjective estimates of the potential volatility of estimated cash flows over the functional life of the machine. Subsequently, sensitivity analyses would be used to examine the sensitivity of the real options value to changes in the value of volatility selected.

6.6.2 Historical

Historical volatility is the statistical measure of previous equity price movements. Empirical estimates of historical volatility are based upon recently observed market value fluctuations. For the purpose of construction automation investment analysis, historical volatility may be calculated from the measuring the volatility of the FTSE Construction and

Building Materials index over a time period equal to the time to expiration of the real option being valued. Alternatively, if the investing company is a public limited organisation, historical equity prices may be used.

To estimate historical volatility using historical data, it is necessary to obtain observations at fixed time intervals; typical intervals of time would be trading days. Empirical research suggests that trading days should be utilised in calculating historical volatility (Hull 2000). It is assumed that there are 252 trading days in a year. Volatility changes over time. Historical data that is too old may not be relevant for predicting future price fluctuations. According to Hull (2000), it is appropriate to use closing prices for daily data over the most recent 90 to 180 trading days. Within the real option analyses, 1260 trading days (60 months) have been utilised due to the data being applied to real options with expiration time greater than one year (approximately 5 years).

To estimate historical volatility using historical data, it is necessary to obtain observations at fixed time intervals; typical intervals of time would be trading days. It is assumed that there are 252 trading days in a year. Utilising the methodology outlined by Amran and Kulatilaka (1999), historical volatility has been calculated over a five-year period (1995 to 2000). A sample from the historical volatility calculations is presented in Table 6.3. The continuously compounded return is calculated as:

$$u_t = \ln\left(\frac{A_t}{A_{t-1}}\right) \tag{6.10}$$

where u_t is the return between $t-1$ and t , and
 A_t is the asset value at time t .

Historical volatility is then calculated using the expression for calculating standard deviations:

$$\sigma = \sqrt{\frac{\sum (u_t - \bar{u})^2}{(n-1)}} \quad 6.11$$

where \bar{u} is the mean of the price ratio.

The historical time-period used to estimate volatility must be no less than the time to expiration of the real option. This will therefore capture the infrequent movements in the underlying asset, which in this case is assumed to be the surrogate market index. The standard deviation is then annualised by multiplying by the square root of the number of trading days in the year, i.e. 252.

6.6.3 Implied

This is the volatility implied by an option price observed in the market. An iterative search procedure may be utilised to calculate the implied volatility of a stock if the other option pricing parameters are known. Implied volatility can be calculated by treating the Black-Scholes model as a function of volatility, with C , S_0 , X , r and t being known. It is therefore a non-linear equation with one unknown parameter, σ . The Black-Scholes formula can not be rearranged to provide a formula for calculating σ . Therefore, an iterative search technique such as the Newton-Raphson method must be adopted.

However, unlike the oil and gas industries, construction industry volatility does not depend upon the price of an individual commodity, which is continuously traded within international financial markets. Therefore, the use of existing financial derivatives market values to calculate implied volatility may present significant difficulties for real option valuation within the construction sector.

6.6.4 Simulated

Alternatively, a proxy for real option volatility may be found using financial risk analysis and combining the results with a Monte Carlo simulation of the value of the real option. The value adopted for the investment volatility may assume a probability distribution function, which is then sampled randomly to provide a real option value profile. The simulated value profile provides an indication of the extent to which the value of the option may vary depending upon the volatility of the investment.

6.7 Real option premium

Initially, an investment appraisal must be undertaken to investigate the potential value of the assets under consideration. Understanding of the technology and its subsequent operational requirements will take the form of preliminary research (desk-studies). By making relatively small resource commitments at the initial stages of strategic option developments, firms may reduce the sunk costs in case of project abandonment (Anderson 2000). Any costs associated with investigating the potential value of an investment opportunity may be classed as the premium, which must be paid prior to the execution of a real option. The option premium may be relatively insignificant in relation to the total

investment cost, but the upside potential for the preliminary investigative work is the essence of real option valuation.

6.8 Japanese construction automation technology strategies

Japanese companies have rarely developed distinct strategic positions with most firms imitating and emulating one another (Porter 1996). Assisted by favourable taxation policies, Japanese general contractors have been actively encouraged to fund private technical research institutes and conduct extensive research and development programmes. Quality of work, management efficiency and technological prowess are all central to Japanese contractors marketing strategies. Japanese contractors compete on a technology (quality) basis, instead of price competition as in the case of North America and Europe (Pries & Janszen 1995). Competitive advantages lie mainly in their broad expertise and technological sophistication (Fraser & Zarkada-Fraser 2001). A combination of massive contracting organisations with strong manufacturing links, a construction system in which the contractor has full control over the design process, and market driven technological innovation has led to substantial investment in construction related research and development.

The Japan Robot Leasing Company was established to encourage the widespread use of industrial robotics amongst small and medium sized companies within Japan. Special financing was made available by the Small Business Finance Corporation and the People's Finance Corporation to assist small and medium sized organisations in the introduction of robots that enhanced worker safety (Porter *et al* 2000). Special depreciation allowances were introduced to allow investors to write off 25% of the value of high performance robots in their first year of use. These allowances were subsequently reduced as the technology

became more established. Japanese government policy stimulated early demand but also demand for more sophisticated machines, which spurred manufacturers to innovate and upgrade (*ibid* 2000).

As Table 6.4 indicates, the major Japanese general construction contractors have been actively involved in the development of a broad range of automated technologies, ranging from single task systems to complex high-rise automated construction systems. Rather than specialising in a specific technology, it is evident that the Japanese contractors have actively pursued a range of construction automation research, development and implementation strategies to match competitors technological capabilities. Imitation of competitors' technology strategies eliminates the potential for first-mover advantages. However, the costs of implementing innovative technology may be reduced by learning from industry leaders experiences and, subsequently, avoiding research and development costs.

According to Porter (1985), changing the technology of a value activity (i.e., construction) can influence the drivers of cost or uniqueness in that activity. Even if the technological change is imitated, it will lead to a competitive advantage for a firm if it skews drivers in the firm's favour. Porter (*ibid*) provides an example of a new assembly process that is more scale-sensitive than the previous process, which benefits the large market share firm that pioneers it even if competitors eventually adopt the technology.

Despite the obvious lack of distinct research and development strategies and the emulation and imitation of competitors technology positions, the Japanese general contractors have developed and exercised an extensive selection of learning, abandonment, timing and strategic growth options. These strategic technology options may provide extensive future

opportunities for profit and growth. However, these strategic technology options have emanated from over two decades of intensive R&D stemming from copious investment from the private sector. Within Japanese construction companies, a continuing technological leadership position typically results in a prominent reputation, which is a precious intangible asset the often appears to be at the root of commercial success (Kangari & Miyatake 1997). Furthermore, innovations that provide significant intangible benefits may contribute to the competitive positioning of the firm (Slaughter 1998).

6.9 Technology strategy

Technological innovation may be a potential source of profit and strategic growth for UK construction organisations. Hampson and Tatum (1993) concludes that the diligent application and implementation of the technology strategy concept may provide the foundation for the creation of substantial competitive advantages. Commercial benefits may include productivity improvements, construction cost reduction, access to new markets and increased share of existing markets. A firm that can discover a better technology for performing an activity than its competitors, therefore, gains competitive advantage (Porter 1985).

The act of technological invention rests with machine manufacturers. However, the act of innovation rests with the end-users of those inventions. The choice of which plant and machinery is to be used on site rests with the contractor (Langford & Male 2001). However, with the advent of the plant and machinery hire sector and contractors minimising their commitment to fixed capital, the plant and machinery available for hire will dictate the choice of plant and machinery available to contractors. Subsequently, the

plant hire sector may play a more dominant role in the deployment of innovative plant and machinery than traditionally envisaged.

Specialist sub-contractors engage in work, which is of a similar nature from project to project. Greater work repetition increases the potential for these organisations to extensively use automated technologies. Subsequently, it may be more appropriate for such organisations to consider the outright purchase use of mechatronics systems. However, consideration must be given to maintenance contracts with the manufacturers and the provision of adequate training for operators and technicians.

Design and Build contractors are in an ideal situation for implementing automated construction technology. With centralised control over the design and construction of a project, contractors may be in a position to select innovative construction process technologies in conjunction with incorporating the necessary design provisions. However, with the extensive utilisation of sub-contractors and labour-only subcontracting the incentive to replace labour with advanced mechanisation may be lost.

Plant-hire organisations must also keep abreast with the latest development in construction plant and machinery in order to remain competitive within their operating markets. They have an incentive to provide innovative plant in that they are to retain, or even expand, their customer base. Subsequently, investment in innovative plant and machinery may be a necessary strategy for their survival and growth within the sector.

6.9.1 Technology observation and transfer

Innovation within construction firms' requires active pursuit of novel equipment, tools, instrumentation and IT systems. The sharing and exploitation of knowledge is the key to the development of new products and innovation within the construction sector. Identification, understanding, evaluating and assessing the experiences and practices of overseas technological innovation may facilitate the successful transfer of pre-competitive technologies. Furthermore, the investigation of innovative technologies successfully introduced into other industrial sectors may open further possibilities for technology transfer.

Implementing pre-competitive 'tried and tested' technologies from international machine manufacturers may provide opportunities to implement construction automation without expensive and prohibitive R&D costs. The Construction Industry Council claimed that it would be more cost effective for construction firms to acquire existing technology from a variety of low cost sources, rather than attempt to create new technology themselves (Gann & Simmonds 1993). Chapter 3 examined existing technological capabilities and highlighted appropriate technologies for possible implementation within UK construction and civil engineering operations. Furthermore, Section 5.6 described the role of 'technology gatekeepers' in the identification of suitable pre-competitive technologies.

6.9.2 Technology strategy depth

As described by Hampson and Tatum (1999), the depth of a technology strategy encompasses the number of technological options the firm has available. Furthermore, they commented that depth of a technology strategy is determined by the intensity of resource

expenditure. There must be commitment to specific innovations and to the extent to which these may be introduced to the firm's operations. The greater the number of technologies to be investigated and the greater their proposed role in the operations of the firm, the greater the depth of the technology strategy.

The number of technology investment real options that a firm considers provided an assessment of the technology strategy depth. Furthermore, commitment to resource consumption is analogous to real option premiums. Real option premiums incorporate the cost of any preliminary investigative work undertaken prior to the exercise of the real option. The number of technology investment options generated will be dependent upon the initial investigative work undertaken by the organisation's technology gatekeepers.

6.10 Real option valuation models

In this section, the specific valuation models are developed for a series of real options available when considering construction automation investment opportunities. The significant feature common to the real option valuation models presented is their positive valuation of investment opportunities that, using traditional DCF techniques, would not be viable.

Figure 6.6 presents a strategic decision, implementation and evaluation model for construction automation investments. Specifically, the model incorporates the real options, which may become available at the various stages of the implementation and evaluation process.

In the present study, the following classification of real options are used to examine construction automation investment opportunities:

- *pioneer learning options* – these incorporate speculative investments, which may provide significant opportunities to learn new processes or procedures;
- *timing options* – these incorporate the ability to wait and examine the actions of competitors prior to the implementation of a new technology;
- *abandonment options* –if an innovative technology appears to not be providing the perceived benefits and is consuming resources, there may be significant value associated with abandoning the technology and realising the re-sale value on the second hand markets;
- *strategic growth options* – implementing existing technologies may provide opportunities for the future deployment of more technologically sophisticated systems as a when they become available, and
- *switching options* – there may be value associated with having the flexibility to switch between traditional construction plant and machinery and mechatronics technology and vice versa.

The above real options may interact and a single investment opportunity may give rise to a selection of real option scenarios. Within the present study, each category of real option is considered exclusively. Many of the value characteristics presented within the following real option valuations are not quantified using traditional DCF appraisal techniques. However, it is these specific characteristics which contribute significant value to construction mechatronics investment.

6.10.1 Pioneer learning ventures

The capacity of the firm to learn is, arguably, the most important determinant of its ability to innovate on projects (Winch 1998). Improvements in technology and organisation are correlated through experiential learning (Kogut & Kulatilaka 2001). Uncertainty regarding maintenance expenditures, productivity, reliability, operational and technical requirements may lead to valuable learning options being exercised. The ability to defer investment and gain further understanding of the on site requirements of automated technology may be valuable. Waiting to commit funds may preserve the capital expenditure required and protect the company from expensive errors. The cost of early adoption may be more expensive than waiting until a technology is succeeded by a following generation (Grenadier & Weiss 1997). However, the early adoption of technologies may facilitate pre-emptive understanding of the technology. These acquisitions may prove to be an invaluable staging post for future value creation. Innovators may move into new markets or products only after market viability is proven (Langford & Male 2001). Computer integrated manufacturing technology was often adopted earlier rather than later to provide the opportunity of learning by doing. This would allow future innovations to be rapidly implemented when they became available.

Grenadier and Weiss (1997) incorporate the value of learning by acknowledging that the cost of upgrading from an existing innovation is less than the cost of leapfrogging to a future innovation, without the benefit of learning. The premium paid for a learning option allows the owner to reduce uncertainty by undertaking an investment: in other words paying to learn (Copeland & Keenan 1998). Therefore, plant hire and construction firms initially investing in tele-operated systems will be able to migrate cheaply and rapidly to new innovative automated technology. Plant operators and maintenance engineers will be

comfortable with the basic technology and be better prepared for dealing with future innovations.

The companies that are enduringly successful will be those that begin as early as possible to define and embody in their activities a unique competitive position (Porter 1996). With insight into the likely pattern of technological evolution, a firm may be able to anticipate technological change and invest early to reap competitive advantages (Porter 1985).

During the implementation of the Shimizu Corporation's SMART system, the project became a major attraction. Site visitors included clients, architects and engineers, and international R&D groups. The main benefit from such a reputation was the greater ability to attract potential clients through superiority in technological innovation, improved safety and increased site productivity (Kangari & Miyatake 1997). Porter (1985) highlights the potential sources of first mover advantages. In relation to construction automation investment opportunities, those of relevance were as follows:

- *reputation* – a firm that invests first may establish a reputation as an industry leader and create a reputation that other plant-hire or contractors may have difficulty overcoming;
- *proprietary learning curve* – a firm that invests first may gain a cost or differentiation advantage if there is a proprietary learning curve in the value activities that are affected by the early move, and
- *definition of standards* – a first mover may define the standards for working practices, forcing later movers to adopt them.

The gradual introduction of innovative technology allows operators and site engineers time to discover the strong and weak points of the operating capabilities of the systems in question. This is also wise human resource management because it assists in mitigating employee's misconceptions of the new technology (Foulkes & Hirsch 1984).

However, there are significant sources of uncertainty when considering pioneer learning ventures. These may include:

- gaining regulatory approvals for the use of automated construction technologies on construction projects;
- contractors demand for such technologies;
- technological obsolescence and discontinuities (the inability to respond to major shifts in the available technologies due to fixed capital);
- low cost imitation;
- developing appropriate skill base for machine operations, maintenance and repairs, and
- the high costs associated with importing machines and spare components.

To accelerate the introduction of automation and robotics in the construction process, there is a need for a number of test beds where the integration process of IT, machines and human resources may be demonstrated (Poppy 1994). Specifically, Obayashi (1992) concludes that efforts are needed to accumulate and analyse relevant data from repeated experimental execution of works and performance records.

6.10.2 A timing option

The ability to defer an investment gives rise to two additional sources of value. Firstly, the option to earn interest on the deferred expenditure and, secondly, during the deferral period the asset value may change and affect the investment decision for the better (Luehrman 1998). The latter source of value may stem from future growth of the market, changes in the factor prices or improvements in the technology itself. The length of the investment deferral period is dependant on the rate at which labour wages and the variable costs associated with the technology enhance or reduce the financial feasibility of the technology. Investment timing dilemmas of this nature are appropriately examined within the ROP framework.

The benefits of a late adoption strategy for innovative construction technology lower capital costs (lower borrowing and optimum scrapping), learning from the experience of other users and the cumulative improvements that accrue to later knowledge and competence (Deiaco, Hörnell & Vickery 1990). The cost of early adoption may prove to be more expensive than waiting until a technology is succeeded by a following generation (Grenadier & Weiss 1997). Alternatively, the cost of early adoption may be greater than waiting until another competitor (plant-hire firm) has purchased and implemented similar technology.

The binomial tree pricing model provides a simple and efficient numerical procedure for valuing real timing options, where early exercise may be beneficial. A timing option may be valued numerically by mapping the proposed investment opportunity as an American call option using the binomial tree approach (Cox *et al* 1979). American options can be exercised at any date prior to the expiration date of the option. This means that as a result

of a plant hire firm monitoring market demand, the status of the labour markets and the development of the technology they may at any stage chose to purchase the machine. Using the Binomial model to value automated construction technology infers that Δt is equal to a short time period within one fiscal year. The time-period over which the deferral option is alive depends upon the length of time that management wishes to consider the proposed investment opportunity. Real options are open-ended, the time to exercise is non-specific and the option can be exercised at any time. Mann *et al* (1992) suggests that it is reasonable to expect that within five years, sufficient information will have arisen to determine whether a strategic investment is viable.

In practice, the life of an option is divided into 30 or more time steps of length Δt . In each step, there is a binomial stock price (NPV of project cash flows) movement. The parameters u and d are chosen to match the estimated cash flow volatility.

Table 6.5 presents the timing option parameters used to model the value of a hypothetical construction automation investment opportunity. Further to estimating the operating, ownership, and the subsequent rental cash flows over the economic life of the machine, the net present value of the investment may be estimated. From conducting financial risk analyses, the standard deviation (volatility) of a risk profile may be obtained. The net present value of the investment is assumed to be equal to £6000, the exercise price incorporates the purchase price of the machine and the associated set-up costs. The risk free interest rate is 6.5% and is derived from the yield to maturity on short dated treasury stock. Volatility is assumed as 40% and the investment deferral period is assumed to be one fiscal year ($\Delta t=0.20$). Equation 6.6, 6.7, 6.8, and 6.9 are used to derive the remaining parameters.

Figure 6.7 depicts a five step binomial tree for the hypothetical timing option, where at each node the top section indicates the underlying value (NPV of project assets) and the lower indicates the value of the call option (timing option). The shaded nodes indicate where the option should be optimally exercised.

The value of the call option at the final nodes is calculated as $\max(0, S_t - X)$. The value of the call option at node *B* is calculated as:

$$(p \times \text{£}686.36 + (1 - p) \times \text{£}33.04)e^{-r\Delta t} = \text{£}360.39 \quad 6.12$$

At node *B*, if the option is held it will be worth £360.39. However, if the option is exercised, it will have a value of -£2824.70 (£7175.30 - £10,000 = -£2824.70). Therefore, it is not optimal to exercise the option at this stage and would be more valuable to continue holding the unexercised option. Nodes *G*, *K*, *P* and *Q* indicate that early exercise would be optimal. Therefore, due to an increase in the value of the underlying (the investment cash flows), the value of the call option has exceeded the exercise price and the option is in-the-money. At this stage it would be profitable to exercise the call option early and, therefore, invest in the selected technology.

6.10.3 An abandonment option

All innovations involve technological and economic risks at all stages of diffusion and that decisions to reject an innovative technology may be entirely justifiable at any stage (Cusack 1992). If demand for automated plant and machinery appears to be weaker than anticipated,

plant hire organisation may wish to contract their investment and resale the machines on the second hand market. The option to contract, just as the option to expand may be particularly valuable in the case of new product introductions in uncertain markets (Trigeorgis 1993). Abandonment options are valuable when uncertainty surrounds the uptake of new process technology, and the early stages of implementation may resolve this uncertainty (Busby & Pitts 1998).

Unfavourable labour market conditions in conjunction with poor industry uptake may lead to the abandonment of non-profitable systems. Abandonment options may be valued as American put options. The owner of a American put option has the right, but not the obligation, to sell the underlying asset at the predetermined exercise price prior to the expiry date (Hull 2000). Real abandonment options may be valued using the numerical approach used to model the previously described timing option. However, the value of the option at the final nodes is calculated as $\max (X - S_t)$.

Table 6.6 presents the abandonment option parameters used to model the value of a hypothetical mechatronics investment opportunity. Further to estimating the operating, ownership, and the subsequent rental cash flows over the economic life of the machine, the net present value of the mechatronics investment may be estimated. From conducting financial risk analyses, the standard deviation (volatility) of a risk profile may be obtained. The net present value of the investment is assumed to be equal to £1500, the exercise price is the re-sale value of the machine, assumed to be £1000. The risk free interest rate is 6.5% and is derived from the yield to maturity on short dated treasury stock. Volatility is assumed as 40% and the investment deferral period is assumed to be one fiscal year ($\Delta t=0.20$). Equation 6.6, 6.7, 6.8, and 6.9 are used to derive the remaining parameters.

Figure 6.8 depicts a five step binomial tree for the hypothetical abandonment option, where at each node the top section indicates the underlying value (NPV of project assets) and the lower indicates the value of the put option (abandonment option). The shaded nodes indicate where the option should be optimally exercised.

The value of the put option at the final nodes is calculated as $\max(0, X - S)$. The value of the put option at node O is calculated as:

$$(p \times £122.95 + (1 - p) \times £386.74)e^{-r\Delta t} = £266.61 \quad 6.13$$

At node O , if the option is held it will be worth £266.61. However, if the option is exercised, it will have a value of £266.61 (£1000 - £733.39 = £266.61). Therefore, it is optimal to exercise the abandonment option at this stage rather than continue holding the unexercised option. Nodes N , O , T and V indicate that abandonment would be optimal. Therefore, due to a decrease in the value of the underlying (the investment cash flows), it is optimal to abandon the implementation project, i.e. the put option is '*in-the-money*'. At this stage it would be profitable to exercise the put option, abandon the implementation project and realise the re-sale value of the machine in the second hand plant and machinery market.

If market conditions decline and the machine becomes uneconomical, management could abandon current operations and realise the resale value of the machine and other assets in second hand markets. This option framework is of particular interest to the construction plant-hire sector as the deployment of construction mechatronics involves the introduction of new technology within an uncertain market (uncertain demand).

6.10.4 Strategic growth options

A compound option is an option-on-an-option. These instruments are often used by multinational corporations to hedge foreign exchange risk incorporated within overseas acquisitions when the success of the acquisition is uncertain. Sophisticated speculators use compound options to speculate on the volatility of volatility.

Busby and Pitts (1997) conducted a survey of senior finance officers within FTSE 100 firms. They examined the implementation of real option-pricing within decision-making practices. They concluded that the most common and important types of real option were those that provide firms with flexibility over postponement and growth, that is being able to carry out further developments if the current one proved successful. Growth options may be considered as pioneer ventures. Typically, these are projects with a high investment outlay and relatively low initial net cash flows (Kemna 1993). They dominate the equity value of small, high-growth companies marketing innovative products and integrate capital budgeting with long range planning (Kester 1984). In a sense, the negative NPV of the pioneer venture is part of the cost of buying this growth option (Kemna 1993).

The consequence of an innovation investment decision has ramifications on the future options available to firms (Grenadier & Weiss 1997). Sustainable competitive advantages may result from utilising novel technology which in turn may increase the reputation of the firm and enhance market positioning. Positioning technology can provide advantages based upon offering new products in novel markets or developing distinctive competencies (Hampson & Tatum 1999). Strategic investment, in conditions of uncertainty, may be viewed as a commitment to a more aggressive future strategy (Kulatilaka & Perotti 1998).

If successful, innovative technology implementation may provide a leadership position by creating competitive advantages; then, to invest or implement an “unprofitable” and “risky” pre-matured technology may be justified by considering its strategic value (Ho & Liu 2000). The value of construction automation may not be derived from directly measurable cash flows, but rather from unlocking future growth opportunities. Growth opportunities for plant hire organisations and construction contractors may take the form of new construction technology, which could facilitate access to new markets. Unless firms undertake pioneer capital investment, it may be argued that they may not be able to implement further innovations in automated construction plant and machinery.

Substantial investment costs may be required to prove construction mechatronics investments. Initial purchase and set-up expenditure may deem the technology financially non-feasible. Further to improvement in industrial implementation, it may prove to be strategically consequential to have a proven record of accomplishment with basic technology in order to maintain and expand the competitive market position of the firm.

Assuming that sequential innovation investments are based upon an initial successful pioneer venture, a strategic growth option may be valued using a compound option pricing formula. Geske (1979) outlined a valuation theory for pricing options on options, or compound options. The derived compound option valuation formula considered a call option on an underlying, which itself is a call option. Within a real option-pricing framework, the first option is a pioneer venture, which if successful facilitates further capital investment and possible corporate growth.

A compound option has two exercise prices and two expiration dates. Let $C(S, t)$ and $\tilde{C}(S_{T_1}, T_1)$ denote the values of the compound and the underlying call option respectively, where S and S_T are, respectively, the asset price at the current time t and the asset price at the first expiration time. On the first exercise date, T_1 , the holder of the compound option is entitled to pay the first strike price, X_1 , and receive a call option. The call option gives the holder the right to buy the underlying asset for a second strike price, X_2 , on the second exercise date, T_2 . The compound option will only be exercised on the first exercise date only if the value of the option on that date is greater than the first strike price.

Assuming geometric Brownian motion for the underlying asset (NPV of project cash flows), a closed form analytical solution for the valuation of European compound options, in terms of the bivariate normal distribution function, can be found (Kwok 1998). The value, at time zero, of a European call option on a call option is:

$$C(S, t) = S N_2(a_1, b_1; \rho) - X_2 e^{-r(T_2-t)} N_2(a_2, b_2; \rho) - X_2 e^{-r(T_1-t)} N_1(a_2) \quad 6.14$$

where

$$a_1 = \frac{\ln\left(\frac{S}{S^*}\right) + \left(r + \frac{\sigma^2}{2}\right) T_1}{\sigma \sqrt{T_1}} \quad 6.15$$

$$a_2 = a_1 - \sigma \sqrt{T_1} \quad 6.16$$

$$b_1 = \frac{\ln\left(\frac{S}{X_2}\right) + \left(r + \frac{\sigma^2}{2}\right)T_2}{\sigma\sqrt{T_2}} \quad 6.17$$

$$b_2 = b_1 - \sigma\sqrt{T_2} \quad 6.18$$

The function, $N_2(a,b;\rho)$, is the cumulative bivariate normal distribution function and $N_1(a)$ is the cumulative standard normal distribution function. $N(a,b;\rho)$ is the probability that, for two random variables having a bivariate normal distribution with correlation coefficient ρ , the first variable takes on a value less than or equal to a and the second variable takes on a value less than or equal to b . Drezner (1979) provides a simple and efficient computation for the bivariate normal integral based on the direct computation of the double integral by the Gauss quadrature method. The technique calculates $N(a,b;\rho)$ to four-decimal-places.

If $a \leq 0$, $b \leq 0$ and $\rho \leq 0$:

$$N(a,b;\rho) = \frac{\sqrt{1-\rho^2}}{\pi} \sum_{i,j=1}^4 A_i A_j f(B_i, B_j) \quad 6.19$$

where

$$f(B_i, B_j) = \exp\left[a'(2B_i - a') + b'(2B_j - b') + 2\rho(B_i - a')(B_j - b')\right] \quad 6.20$$

$$a' = \frac{a}{\sqrt{2(1-\rho^2)}} \quad 6.21$$

$$b' = \frac{b}{\sqrt{2(1-\rho^2)}} \quad 6.22$$

Steen *et al* (1969) provide the values of the Gauss quadratures, A_i and B_i for $k = 4$.

The variable S^* , is the value of the estimated cash flow at time T_1 for which the machine price at time T_1 equals X_1 . If the estimated cash flows are above S^* at time T_1 , the first option will be exercised; if it is not above S^* , the option will expire worthless. The value of the underlying call option may be calculated using the Black-Scholes formula. In particular, when $t = T_1$:

$$\tilde{C}(S_{T_1}, T_1) = S_{T_1} N_1(d_1) - X_2 e^{-r(T_2 - T_1)} N_1(d_2) \quad 6.23$$

where

$$d_1 = \frac{\ln\left(\frac{S_{T_1}}{X_1}\right) + \left(r + \frac{\sigma^2}{2}\right)(T_2 - T_1)}{\sigma\sqrt{(T_2 - T_1)}} \quad 6.24$$

$$d_2 = d_1 - \sigma\sqrt{(T_2 - T_1)} \quad 6.25$$

$N_1(d_1)$ and $N_1(d_2)$ are standard cumulative probability distribution functions for a variable that is normally distributed with a mean of zero and a standard deviation of 1.0. The critical value for S , denoted by S^* , above which the compound option will be exercised at T_1 is given by solving the non-linear algebraic equation:

$$\tilde{C}(S^*, T_1) = X_1 \tag{6.26}$$

Estimates for the following input parameters are required to value a strategic growth option:

S = Net present value of the cash inflows of the investment as of the second expiration date (T_2).

σ = Volatility of the estimated cash flow (σ of risk profile).

X_2 = Net present value of further capital expenditure.

X_1 = Net present value of initial investment.

r = Risk-free interest rate (3-mnth Treasury bills).

T_1 = Time to maturity of first option (initial pioneer option or trial implementation period).

T_2 = Time to maturity of second option (i.e. further investment in more machines or similar technology).

$N_2\left(a_1, b_1; \sqrt{\frac{T_1}{T_2}}\right) =$ Bivariate normal distribution function with a_1 and b_1 as upper and lower integral limits, and

$$\text{correlation coefficient, } \rho = \sqrt{\frac{T_1}{T_2}}$$

For example, suppose that a plant hire organisation is considering a construction automation investment opportunity that requires an initial investment of £50,000. This initial investment includes the initial purchase price of the machine and all associated implementation costs. Assuming the company conducts a pioneer venture to investigate the implementation of the new technology, the underlying call option may have an assumed time to expiry of one fiscal year. Following a successful pioneer venture, the company may invest in similar machines or expand the range of automated technology available for hire. The further investment may then be assumed as the second exercise price, with a second expiry date. Within the presented worked example, it is assumed that £150,000 will be invested if the initial pioneer venture is successfully exercised.

On the first expiration date (T_1), the owner of the compound option has the right to buy the underlying call option (undertake and complete the pioneer venture) at the first exercise price (X_1). Exercising the underlying call option then bestows the right to undertake the future capital investment for the second exercise price (X_2) on the second expiration date (T_2).

Table 6.7 presents the hypothetical values used to appraise a strategic construction automation investment opportunity. The net present value of the investment cash flows, S , is assumed to equal £250,000. The value of the estimated project cash flows for the expansion option may be determined by conducting a financial risk analysis of the associated ownership and operating cost variables (Taylor *et al* 2000). The constructed risk

profile standard deviation of returns may also be used to provide an estimate of the volatility of the project cash flows. Within the presented growth option worked example, the volatility of the project cash flows, σ , is assumed to equal 40% (0.40). Should the initial pioneer option be exercised, and the further growth option exercised, the investment opportunity may be valued at £89422.29. This value is dependent upon the current value of the project cash flows and may be subject to variation due to the evolution of the value of the project cash flows.

Within the compound option formula, the flexibility of multistage decision making is accounted for and contributes to the value of the investment opportunity (Kemna 1993). The sequential growth option-valuation methodology is advantageous in aligning consecutive investment opportunities with strategic planning. Options concerning future implementation of automated technology may be contingent upon the exercise of pioneer venture options. Traditional valuation procedures may undervalue investments that incorporate growth options. Contractors and plant-hire organisations may be forfeiting opportunities for profit and growth to be gained from investment in available technology.

The presented real-compound option valuation assumes that strategic mechatronics investment planning is series of compound options – each option depending upon the exercise of the preceding options. The main advantage of a growth option framework is that it integrates capital budgeting with strategic financial planning. Initial investment in first-generation high-tech products may be seen as prerequisites or links in a chain of interrelated projects (Trigeorgis 1993). Following improvement in construction industry implementation it may prove to be strategically consequential to have a proven track record the basic technology to maintain and expand competitive market position.

6.10.5 Switching options: construction process flexibility

Within a broad range of manufacturing operations there exists the ability to shift between labour-intensive and capital intensive technologies (Kulatilaka & Marks 1988). Trigeorgis (1993) described *process flexibility* switching options, which examine the value of altering the production of outputs using alternative inputs. With regards to the operations of the construction industry, process flexibility may infer that a structural element could be constructed using different inputs, i.e. traditional plant and machinery in combination with manual labour or mechatronics technology with reduced labour input. Switching options give the owner the right to switch between two modes of operation for a fixed cost (Copeland & Antikarov 2001). The right, but not the obligation, to alter modes of operation is obtained by paying a switching premium. Switching options may be used to value the possibility of switching between manual and mechanised construction operations, in relation to the arrival of innovative technology. Changing construction processes, depending on input factor prices, may be valued using switching option analysis.

Assuming that a specialist construction sub-contractor is currently using a method of construction, which utilises traditional construction techniques in combination existing plant and machinery. However, the sub-contractor is experiencing increased demand for their services. The availability of an affordable automated system and the possibility of increased labour costs have led the company to reconsider their operations. The following options are available: continue using the traditional technology (mode of operation *A*) or pay a switching premium and consider implementing the alternative mechatronics technology (mode of operation *B*).

Implementing an innovative technology may incur significant switching costs. If a contractor adopts mechatronics technologies through a plant-hire firm, despite not incurring the ownership and operating costs of the machine, there may significant switching costs associated with adapting site operations and the supervision of highly automated processes.

The cost of switching to a new technology may include the cost of hiring skilled operators and maintenance personnel, increased cost of repairs and maintenance due to technological complexity, as well as the initial purchase price of the machine. Alternatively, the cost of switching may be the cost of hiring the innovative technology compared to the original costs, which included traditional machines and human labour. Within the following example, it is assumed that a specialist sub-contractor is considering replacing the plant and machinery that they currently use with a mechatronic system capable of increasing productivity and quality with a reduction in human labour.

The method of valuing operational switching options with compound interactions proposed by Trigeorgis (1996) is implemented to describe the value of switching between traditional construction plant and machinery and automated technology. Switching input technologies not only affects the current decision and cash payoff, but also alters the exercise costs and future switching decisions. In summary, the exercise of an earlier option, i.e. switching technologies in an earlier period, creates a series of new options to switch in the future that are analogous to a compound option (Trigeorgis 1996).

Switching options are path dependent. If there are two possible technologies, which may be used, the optimal action in any future state depends upon the NPV of the technology and current mode of operation. Therefore, a backward dynamic programming process is

required, i.e. one that is both forward and backward looking (Copeland & Antikarov 2001). This solution technique rolls out possible values of the underlying asset (NPV) during the life of the option and then folds back the value of the optimal decisions in the future (Amram & Kulatilaka 1999b).

Table 6.8 outlines the switching option notation and describes each variable. Figure 6.9 shows the switching option pricing model, indicating the different states for the NPV of project cash flows and the subsequent operational process switching decisions. Consider two alternative technologies (A and B), with three decision nodes ($t = 0, 1$ and 2). Let $C_t^s(m)$ be the net present cash flow generated in time period t if found in state s (where $s = +$ or $-$, in time period $t = 1$, or $++$, $+-$ or $-$ in time period $t = 2$) when using technology m ($m = A$ or B). Figure 6.10 shows the time periods and states at each switching node. Figures 6.11 and 6.12 show the hypothetical cash flows generated from the use of two alternative process technology modes (A and B).

The value of flexibility to switch between the alternative technologies, $E(F)$, is greater than the net present value of each of the machines. Therefore:

$$E(F) \geq \max (NPV(A), NPV(B)) \quad 6.27$$

The value of flexibility exceeds that of technology A by the value of the flexibility to switch technologies from A to B , denoted by $F(A \rightarrow B)$.

$$E(F) = NPV(A) + F(A \rightarrow B) \quad 6.28$$

The value of the investment flexibility is the sum of three European call options to switch from A to B , denoted by $S_t(A \rightarrow B)$, in years $t = 0, 1$ and 2 , respectively. Therefore, the value of the flexibility is:

$$F(A \rightarrow B) = S_0(A \rightarrow B) + S_1(A \rightarrow B) + S_2(A \rightarrow B) \quad 6.29$$

Let $I(A \rightarrow B)$ be the cost of switching from traditional technology (A) to mechatronics technology (B). In the presence of these switching costs, the incremental cash flow associated with switching from technology A to B becomes:

$$C_t^s(A \rightarrow B) \equiv \max \left\{ C_t^s(B) - C_t^s(A) - I(A \rightarrow B), 0 \right\} \quad 6.30$$

The incremental cash associated with switching from technology B to A becomes:

$$C_t^s(B \rightarrow A) \equiv \max \left\{ C_t^s(A) - C_t^s(B) - I(B \rightarrow A), 0 \right\} \quad 6.31$$

Using the hypothetical investment parameters outline in Table 6.9, each separate switching option may be valued as outlined below. Assuming that the contractors starts out using technology A , the options to switch technologies immediately may be defined as:

$$S_0(A \rightarrow B) = \max \left\{ C_0(B) - C_0(A) - I(A \rightarrow B), 0 \right\} \quad 6.32$$

At $t = 1$:

$$C_1^+(A \rightarrow B) = \max \{C_1^+(B) - C_1^+(A) - I(A \rightarrow B), 0\} \quad 6.33$$

$$C_1^-(A \rightarrow B) = \max \{C_1^-(B) - C_1^-(A) - I(A \rightarrow B), 0\} \quad 6.34$$

where the option to switch in the first time period ($t=1$) is:

$$S_1(A \rightarrow B) = \frac{(p \times C_1^+(A \rightarrow B)) + ((1-p) \times C_1^-(A \rightarrow B))}{(1+r)} \quad 6.35$$

At $t = 2$:

$$C_2^{++}(A \rightarrow B) = \max \{C_2^{++}(B) - C_2^{++}(A) - I(A \rightarrow B), 0\} \quad 6.36$$

$$C_2^{+-}(A \rightarrow B) = \max \{C_2^{+-}(B) - C_2^{+-}(A) - I(A \rightarrow B), 0\} \quad 6.37$$

$$C_2^{--}(A \rightarrow B) = \max \{C_2^{--}(B) - C_2^{--}(A) - I(A \rightarrow B), 0\} \quad 6.38$$

Where the discounted cash flow in the up state (+) at $t=1$ are:

$$C_1^+(A \rightarrow B) = \frac{(p \times C_2^{++}(A \rightarrow B)) + ((1-p) \times C_2^{+-}(A \rightarrow B))}{(1+r)} \quad 6.39$$

Subsequently, the discounted cash flow in the down state (-) at $t=1$ are:

$$C_1^-(A \rightarrow B) = \frac{(p \times C_2^{+-}(A \rightarrow B)) + ((1-p) \times C_2^{-}(A \rightarrow B))}{(1+r)} \quad 6.40$$

Therefore, the value of switching technologies in the second time period ($t=2$) is calculated using:

$$S_2(A \rightarrow B) = \frac{(p \times C_1^+(A \rightarrow B)) + ((1-p) \times C_1^-(A \rightarrow B))}{(1+r)} \quad 6.41$$

Finally, the sum of the separate option values for switching from $A \rightarrow B$, may be calculated using Equation 6.32, 6.35 and 6.41.

However, the contractor may wish to start out using the mechatronics technology (B) and then consider switching back to the traditional technology if the implementation project is no longer economically viable.

Finally, the optimal technologies for each state must be determined depending upon which mode of operation was initially undertaken by the contractor. As outlined previously, $C_t^s(m)$ represents cash flow at time t (and state s) when using technology, m . $E_t^s(m)$ represents the value of investment as of time t given that state s is entered while using technology m (assuming optimal future switching decisions). $m_t^s(m)$ represents the optimal technology at time t given that state s is entered while operating in mode i ($i=A$ or B). $\hat{E}(E_{t+1}^s(i))$ is the risk neutral expectations operator, using the risk neutral probability p , for the future state.

A technology switch will be optimal only if the value from switching immediately exceeds the value from delaying the potential switching (Trigeorgis 1996). Therefore:

$$E_t^s(A) = \max \left(C_t^s(A) + \frac{\hat{E}(E_{t+1}^s(A))}{(1+r)}, C_t^s(B) + \frac{\hat{E}(E_{t+1}^s(B))}{(1+r)} - I(A \rightarrow B) \right) \quad 6.42$$

where:

$$\hat{E}(E_{t+1}^s(i)) \equiv (p \times E_{t+1}^+(i)) + ((1-p) \times E_{t+1}^-(i)) \quad 6.43$$

Therefore, the following terminal values may be calculated for each state, assuming that technology A is used initially:

$$E_2^{++}(A) = \max (C_2^{++}(A), C_2^{++}(B) - I(A \rightarrow B)) \quad 6.44$$

$$E_2^{+-}(A) = \max (C_2^{+-}(A), C_2^{+-}(B) - I(A \rightarrow B)) \quad 6.45$$

$$E_2^{--}(A) = \max (C_2^{--}(A), C_2^{--}(B) - I(A \rightarrow B)) \quad 6.46$$

For each technology, the discounted risk-neutral expectation of the future benefits from operating using that technology are added to the current cash flow (net of switching costs), then the technology resulting in the greater value is selected. Therefore:

$$E_1^+(A) = \max \left(\begin{array}{l} C_1^+(A) + \frac{p E_2^{++}(A) + (1-p) E_2^{+-}(A)}{(1+r)}, \\ C_1^+(B) + \frac{p E_2^{++}(B) + (1-p) E_2^{+-}(B)}{(1+r)} - I(A \rightarrow B) \end{array} \right) \quad 6.47$$

$$E_1^-(A) = \max \left(\begin{array}{l} C_1^-(A) + \frac{p E_2^{+-}(A) + (1-p) E_2^{--}(A)}{(1+r)}, \\ C_1^-(B) + \frac{p E_2^{+-}(B) + (1-p) E_2^{--}(B)}{(1+r)} - I(A \rightarrow B) \end{array} \right) \quad 6.48$$

Finally, moving to the beginning:

$$E_0(A) = \max \left(\begin{array}{l} C_0(A) + \frac{p E_1^+(A) + (1-p) E_1^-(A)}{(1+r)}, \\ C_0(B) + \frac{p E_1^+(B) + (1-p) E_1^-(B)}{(1+r)} - I(A \rightarrow B) \end{array} \right) \quad 6.49$$

and

$$E_0(B) = \max \left(\begin{array}{l} C_1^-(B) + \frac{p E_1^+(B) + (1-p) E_1^-(B)}{(1+r)}, \\ C_1^-(A) + \frac{p E_1^+(A) + (1-p) E_1^-(A)}{(1+r)} - I(B \rightarrow A) \end{array} \right) \quad 6.50$$

Figure 6.13 and Table 6.10 indicate the optimal technology switching options for the hypothetical investment opportunity. In the presence of asymmetrical switching costs and

the possibility of estimated cash flows either increasing or decreasing in value, there is value associated with having the flexibility to switch between either traditional plant and machinery and mechatronics technology or vice versa. If the contractor initially starts off using traditional technology (A) and the alternative mechatronics technology (B) proves to be more economical and generates sufficient cash flows over and above those realised from using the traditional technology, it will be optimal to switch at nodes A_A , B_A , C_A and D_A . However, if the mechatronic technology it uses initially and the estimated cash flows are realised, it will not be optimal to switch back to using the traditional technology at any stage.

Adopting the above methodology, the contractor has two choices:

1. continue construction using traditional technology for one more period, receive the current cash payoff, plus any expected future benefits, or
2. switch to the alternative mechatronics technology by paying the switching cost in exchange for receiving the alternative technologies cash flow and its expected future benefits.

Therefore, from the valuation of the switching options the value of switching flexibility may be calculated using the expression:

$$NPV(A) + \sum_{t=0}^2 S_t(A \rightarrow B) \tag{6.51}$$

where

$$\begin{aligned}
PV(A) &= 3500 + \left(\frac{(p \times 3928.40) + ((1-p) \times 3118.32)}{1+r} \right) \\
&+ \left(\frac{(p^2 \times 4948.94) + (2 \times p \times (1-p) \times 3500) + ((1-p)^2 \times 2475.28)}{(1+r)^2} \right) \\
&= \text{£}8904.33
\end{aligned} \tag{6.52}$$

Therefore:

$$PV(A) + \sum_{t=0}^2 S_t(A \rightarrow B) = \text{£}8904.33 + \text{£}70.74 = \text{£}8975.07 \tag{6.53}$$

and

$$PV(B) + \sum_{t=0}^2 S_t(B \rightarrow A) \tag{6.54}$$

where

$$\begin{aligned}
PV(B) &= 5500 + \left(\frac{(p \times 6173.20) + ((1-p) \times 4900.21)}{1+r} \right) \\
&+ \left(\frac{(p^2 \times 7776.90) + (2 \times p \times (1-p) \times 5500) + ((1-p)^2 \times 3889.72)}{(1+r)^2} \right) \\
&= \text{£}8904.33
\end{aligned} \tag{6.55}$$

Therefore:

$$PV(B) + \sum_{t=0}^2 S_t(B \rightarrow A) = £15670.04 + 0 = £15670.04 \quad 6.56$$

From the example provided, it is evident that it may be more profitable to switch from mode *A* to mode *B*. However, if the estimated net present values were realised, it may be more profitable to initially start off construction using the alternative mechatronics technology. Importantly, the option to switch process technologies has value. Further to competitors realising significant financial benefits from implementing the mechatronics technology in question, the contractor also has the option of switching to the alternative technology. Alternatively, if competitors do not realise significant financial benefits from using the mechatronics technology under investigation, the sub-contractor may leave the switching option unexercised and remain using the traditional plant and machinery.

A quantitative technique for the valuation of a construction plant and machinery technology switching option has been presented. It is evident that there is significant value attributed to process flexibility switching options. However, the following sub-section describes an important limitation in relation to the effect of hysteresis and the potential for delay in exercising switching options.

6.10.6 Hysteresis and switching options

The term *hysteresis* may be used to describe a lag between the behaviour of a variable, and a change in the factors that influence that variable. The cost of organisational change is related to firms being persistent in their old ways, beyond the recommendations of net present value, because they have become so good at doing the (now) wrong thing (Kogut & Kulatilaka 2001). If the market price of a contractor's output falls below the input

construction costs then production using the methods currently employed will be unprofitable, and there will be an inclination to stop using the current methods. The likelihood of the market price of the contractor's output rising and the potential cost associated with interrupting construction project operations may mean that construction using the uneconomical techniques will continue. Periods of inertia will occur where construction operations continue, using the existing uneconomical techniques, at a short-term loss of profit.

It may be contended that the UK construction industry is currently within a period of labour versus mechatronics hysteresis. It would be more economical and strategically beneficial to implement highly efficient and safety enhancing technology, but uncertainty regarding the technical and operating requirements contributes to the continued use of proven ('tried and tested') traditional construction processes. If inexpensive human labour is abundant and imported mechatronics technology prohibitively expensive, then deploying human labour and traditional plant and machinery may be the more economical option. In every situation, construction and civil engineering contractors must determine the combination of capital resources that are economically favourable.

6.11 Implementing and validating real option-pricing valuation

It is imperative to consider the cerebral and bureaucratic realities of capital investments when utilising real option-valuation techniques. Capital investment decisions often do not involve contracts or have a security underlying them, so there's nothing to trigger expiration of the option or assist in assigning a specific value to it (Fink 2001). Reviewing managerial incentive schemes (reward payment schemes) and defining appropriate procedures for

efficient project exercise and abandonment must be considered when implementing real option-valuation methodologies.

Pinpoint precision is neither an appropriate goal nor a likely outcome of a real option-pricing model and the power of the technique stems from the appropriate mindset rather than from the product of the model (Mauboussin 1999). Their term, unlike that of financial options, is usually open-ended or indefinable. Real option-pricing models do not provide fixed and ready answers, but establish analytical frameworks that allow the evaluation of investment value in different environmental scenarios (Anderson 2000). The high implementation costs associated with automated construction technology may deem pioneer ventures as inherently risky, however, valuing this type of investment opportunity in conjunction with the possible consequential future investment opportunities may incorporate strategic value. Aligning strategic planning with investment decision making may assist the construction sector in realising the potential value of ACT and to facilitate greater investment in both R&D and practical implementation of available technologies.

The real option contemplation process is significant in itself, and leads to potentially valuable awareness of the strategic potential of construction automation investment opportunities. The constructed valuation models aim to outline the application of real option pricing valuation models and provide an illustration of the impact of real option-pricing on ACT strategic investment decisions. It is highlighted that if all managerial flexibility options are heeded, the value of existing ACT investment opportunities may become more enticing.

In order to validate the described real option valuation models, pioneer ventures will have to be undertaken in order to provide quantitative studies of human labour savings and the potential impact upon costs. Having conducted work studies and developed an implementation cost database, the value of project cash flows, implementation, maintenance and repair costs may be used to confirm the predictions made from financial risk analyses and real option valuation. The variation between a real option model value and reality is known as leakage. Leakage is relevant when cash flows move in or out of the underlying asset, affecting the option value (Mauboussin 1999). Sources include explicit positive cash flows (rental and interest) and explicit negative cash flows (storage costs, taxes and fees). Pioneer implementation ventures must be undertaken to realise the true predictive abilities of real option valuation.

6.12 Discussion of results

The widespread use of construction automation is challenged by complex technical and operating risks. Furthermore, the uncertain nature of the ownership and operating costs lead to difficulties in valuing innovative and novel technology. Furthermore, traditional discounted cash flow appraisal techniques alone do not incorporate the managerial flexibility options that are available for potential investors in such technology.

Real option-pricing analysis provides a technique for amalgamating strategic planning with investment appraisal. A timing option was presented in the form of a pioneer venture. It was assumed that the investment opportunity was analogous to an American call option. The binomial tree technique was used to value the call option and calculate the optimum exercise decisions for the real option. It was shown that depending upon the value of the underlying (NPV of project cash flows), it may be optimal to invest in the selected machine

prior to competitive pre-emption. Alternatively, it may be optimal to not invest at all. Investment deferral generates additional value through having the ability to observe competitors actions, allow cash flow uncertainty to prevail and monitor the successfulness of the industrial implementation.

The opportunity to abandon non-profitable operations with automated plant was described. Further to the implementation of innovative plant, it may prove uneconomical to continue using the technology, either due to a lack of demand (from contractors or a lack of suitable projects) or due to the expense associated with using the specific machine in question.

Investment in experimental projects may decrease the prospective cost of transition to future innovations. Having a prior understanding of the associated technical and operational uncertainties may facilitate the successful implementation and application of impending innovations. The value of current investment decisions as possible footings for future investment opportunities may be valued using the described growth option valuation model. An example of a strategic growth option was presented. The strategic growth option example presented indicates that there may be significant value associated with experimentation with construction mechatronics technologies.

Through adding to traditional discounted cash flow analyses, real option-pricing theory provides insight into the examination of strategic automation investment. Real option valuation directly incorporates the value of decision timing and flexibility within strategic mechatronics investment decision analyses. The presented methodologies do not replace the need for strategic managerial judgement, but may assist the development of technology strategies within the construction industry.

6.13 Limitations of real option-valuation

Real option valuation is a dynamic process and decision analysts must update valuation models as new information becomes available. There may be significant costs associated with the monitoring and evaluation of multiple real options.

The presented real option valuation models neglect the effects of competitors actions. Emerging competition or rivalry may create incentives to invest early, as postponement of the investment may result in value erosion. The behaviour of each individual competitor and their influence upon the value of the investment option may be assessed using a game-theoretic approach. The application of this technique is a potential area for further research.

Real option valuation models may be subject to model risk. If the valuation models used are inaccurate or contain errors, there may be a tendency to over value technology investment strategies. However, such investments are seldom based upon quantitative valuation techniques alone and are more often subject to qualitative assessment of strategic value.

Managers must have an understanding of the financial derivatives and the underlying mathematical theory. Therefore, there may be requirements for training in the theory and mathematical techniques required for real option valuation. Organisational constraints may limit the extent to which real options may be exercised. Unlike financial options, there may be a delay period between the decision to exercise a technology investment option and the actual implementation of the investment option.

Unfortunately, the real option valuation models presented within this Chapter are not widely used in industry. Lander and Pinches (1998) proposed that real option based models are not used in corporate decision making for the following primary reasons:

1. The models currently used are not well known or understood by corporate managers and practitioners. Furthermore, corporate managers and practitioners do not have the required mathematical skills to use the valuation models comfortably.
2. Many of the required modelling assumptions are often violated in a practical real option valuation.
3. The necessary additional assumptions required for mathematical tractability limit the scope of applicability.

In order for real option valuation techniques to be widely used within the construction industry, specific attention must be made to the above issues. However, despite these limitations, real option valuation provides a quantitative technique for aligning investment with strategic planning.

6.14 Conclusions

The following conclusions can be drawn from the research presented within this chapter:

1. Construction automation investment opportunities may be undervalued using traditional DCF appraisal techniques alone.

2. Real option valuation compliments NPV analysis when assessing the strategic value of construction automation investment opportunities. Real option valuation considers investment flexibilities, which are neglected using DCF appraisal methodologies.
3. Real option valuation techniques provide quantitative analysis of construction automation investment flexibility. They aid the assessment of strategic investment opportunities and add financial insight to the valuation of possible strategies.
4. Real option valuation methodologies have been successfully adapted for the valuation of strategic automated construction technology investments.
5. The B&S and binomial option valuation models can be used to provide an approximation of the value of strategic construction automation investments.
6. Abandonment options provide a means of valuing possible exit scenarios further to implementation failure or insufficient market demand.
7. Timing options successfully incorporate managerial patience in exercising automated technology investment options. They provide a means of valuing investment deferral and the possibility of pre-competitive investment.
8. Growth options integrate the valuation of automated technology investments and strategic planning.

9. Switching options may be used to value construction process flexibility. Namely, the possibility of switching between traditional plant and automated technologies.
10. Switching options may be used to value contingency planning, in the sense that the objective of such planning is to understand the available alternatives following implementation failure.
11. The cost comparison between mechanised and manual operations may only be undertaken further to pioneer implementation ventures, which will scientifically determine the true operating and ownership cost of the selected innovative technology. Further to obtaining this information, the operating switching options may be valued and the decision regarding the optimal plant and machinery may be undertaken.
12. Despite the limitations of real option valuation, the models presented within this Chapter provide quantitative procedures for the amalgamation of technology investment and technology strategies. Furthermore, the methodologies may be used to provide construction industry professionals with indications of where to focus their efforts in order to maximise the value of their construction automation investment options.

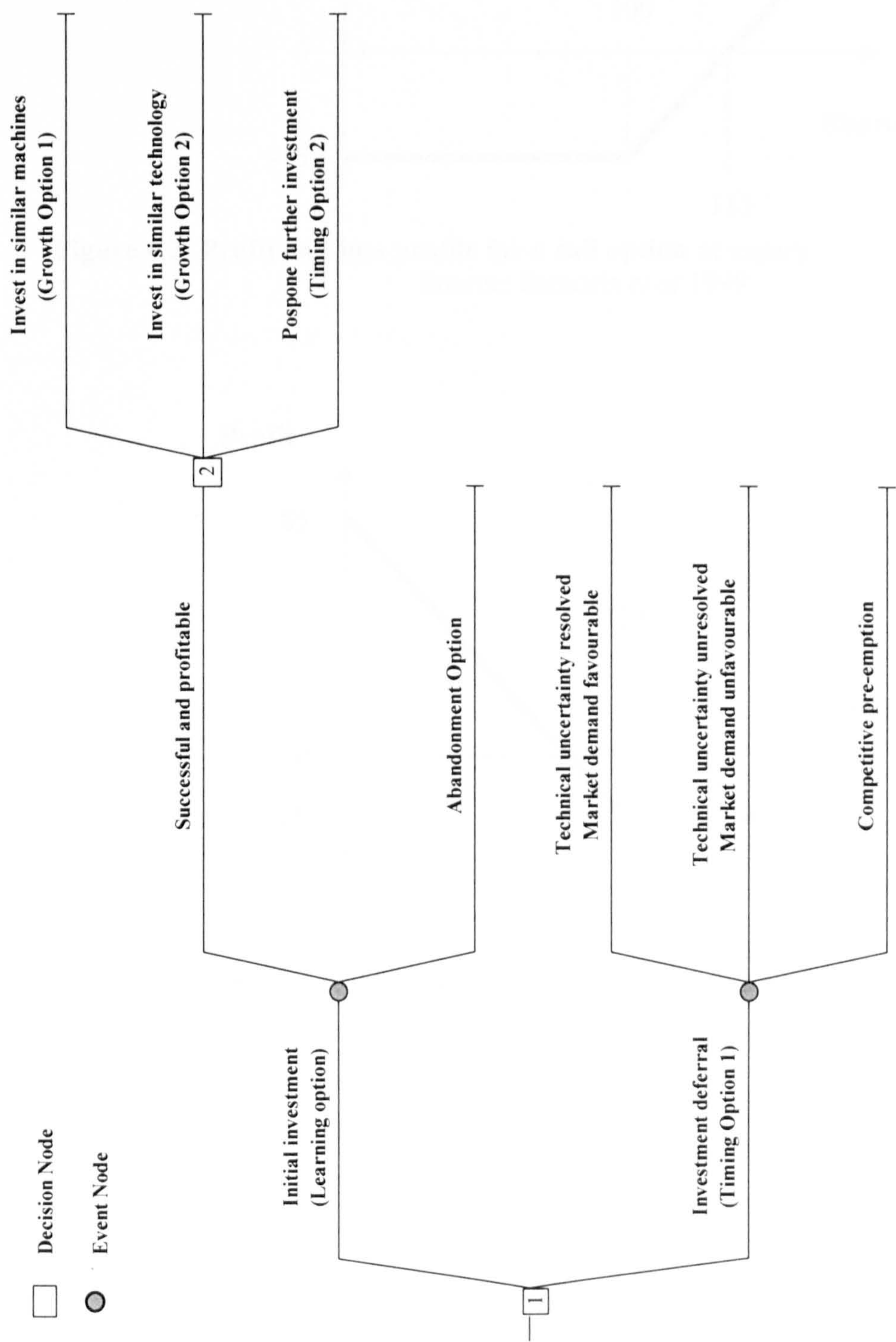


Figure 6.1: Real option decision tree for construction mechatronics investment

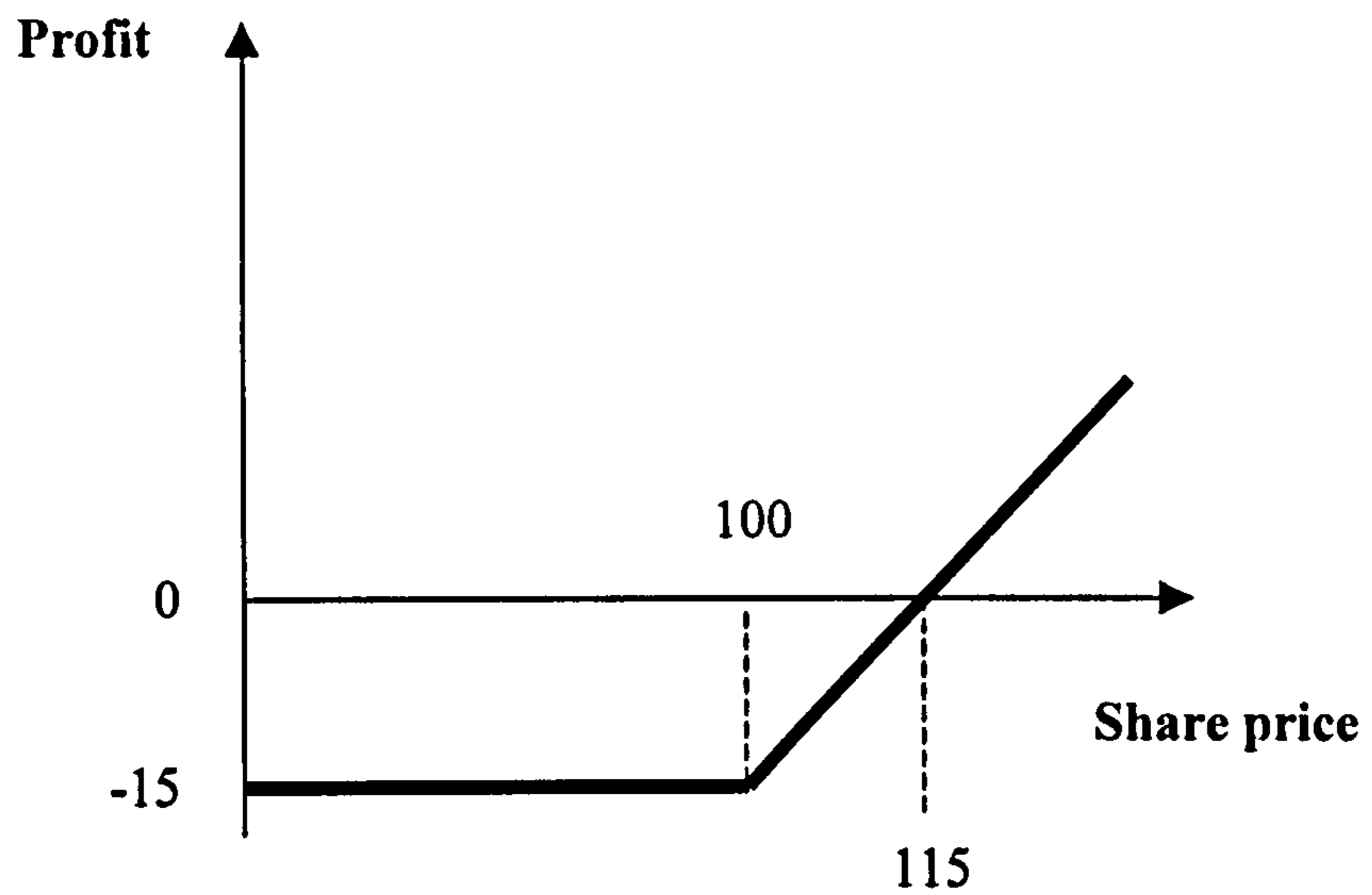


Figure 6.2: Profit and loss profile for a call option at expiry
 Source: Samuels *et al* 1999

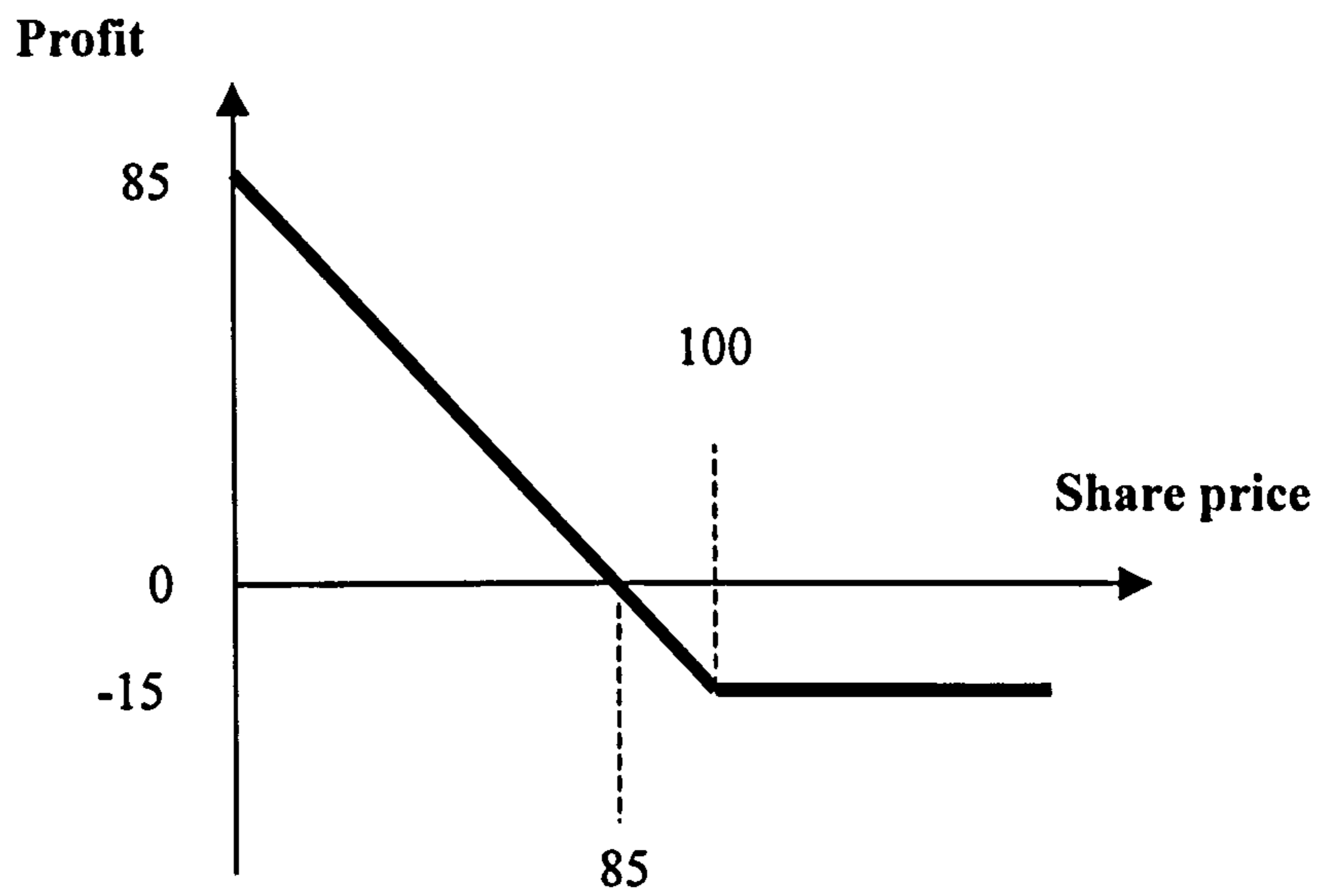


Figure 6.3: Profit and loss profile for a put option at expiry
 Source: Samuels *et al* 1999

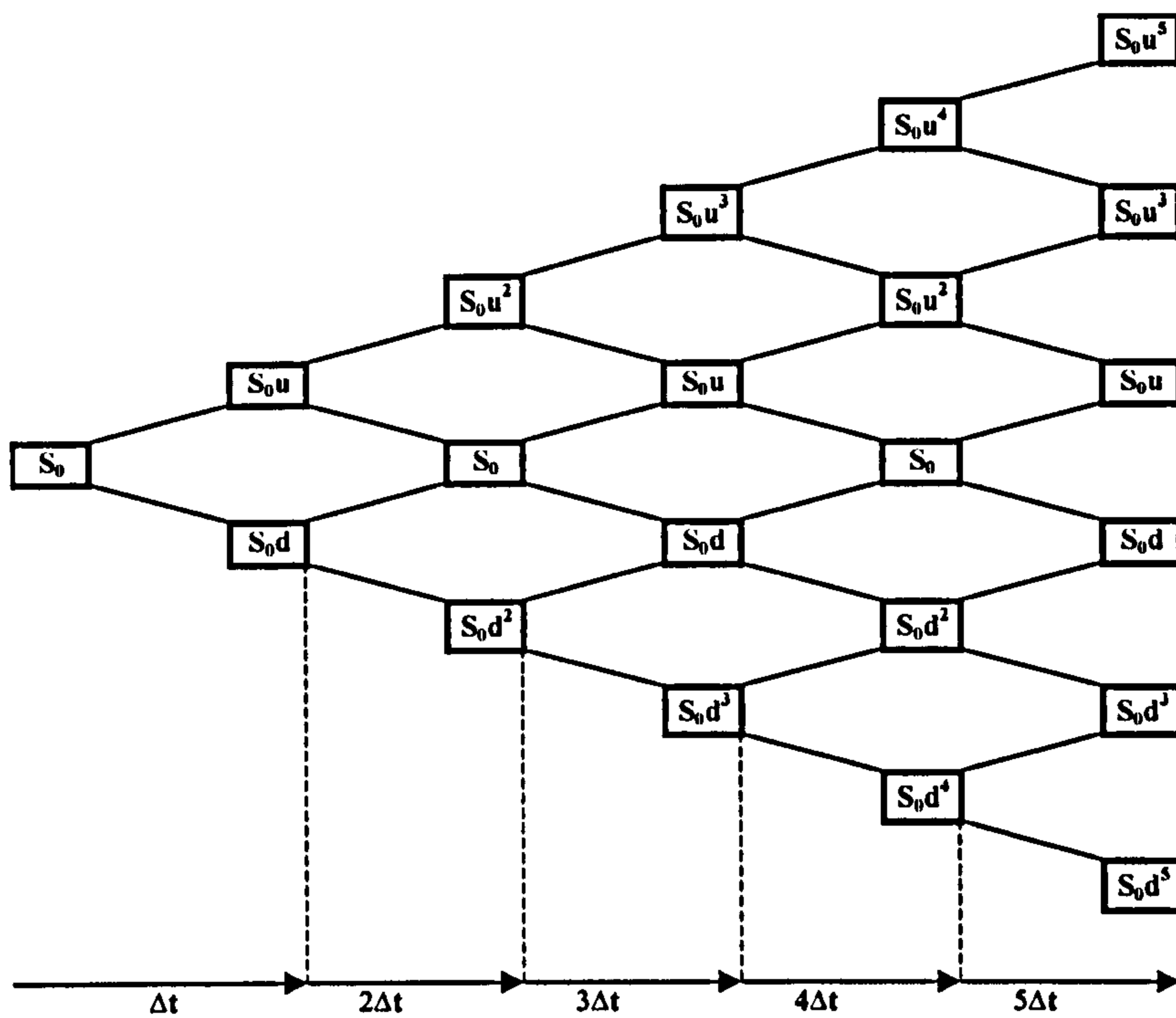


Figure 6.4: Five step multiplicative discrete-time binomial tree
 Source: adapted from Hull 2000

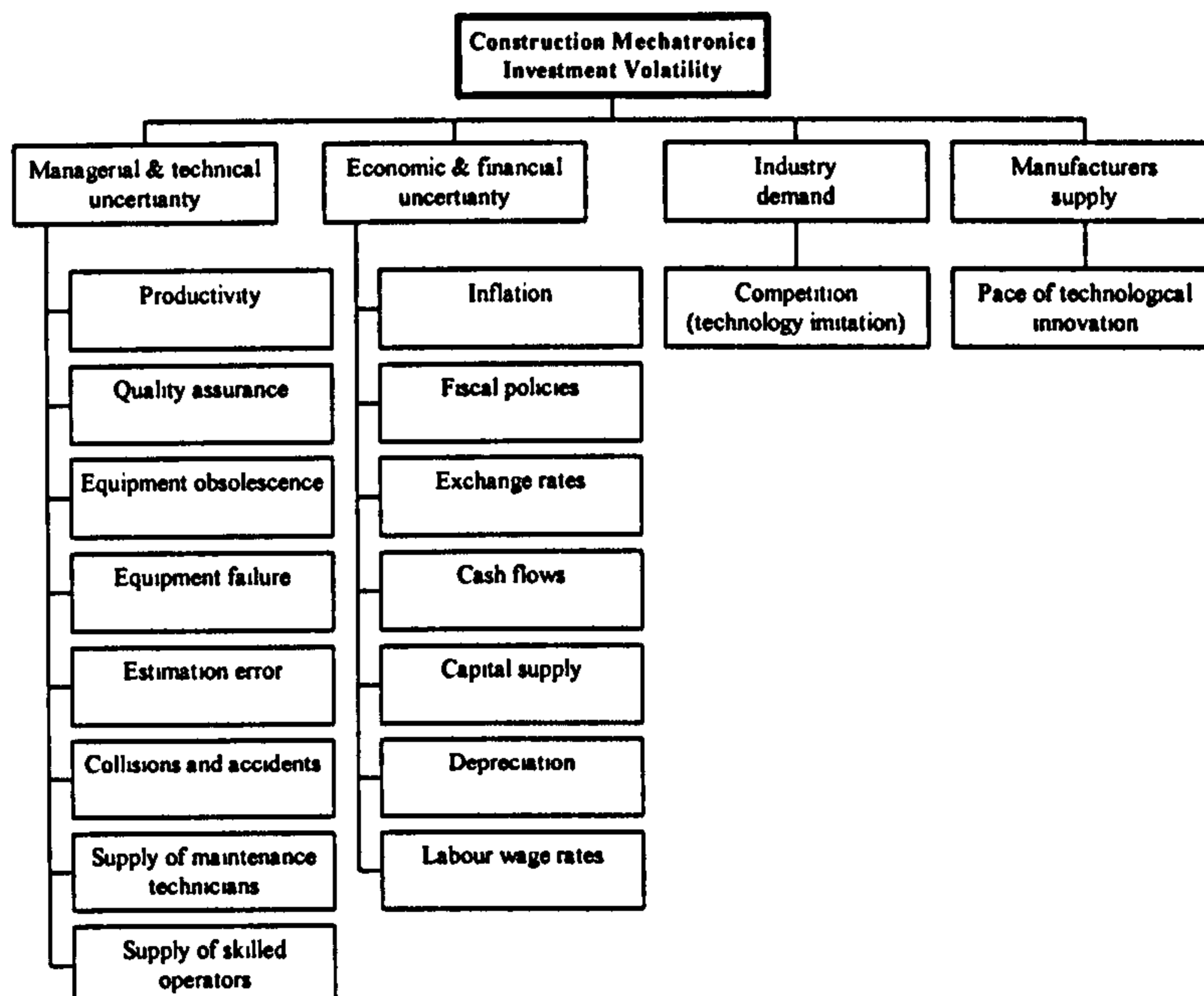


Figure 6.5: Sources of construction mechatronics investment volatility

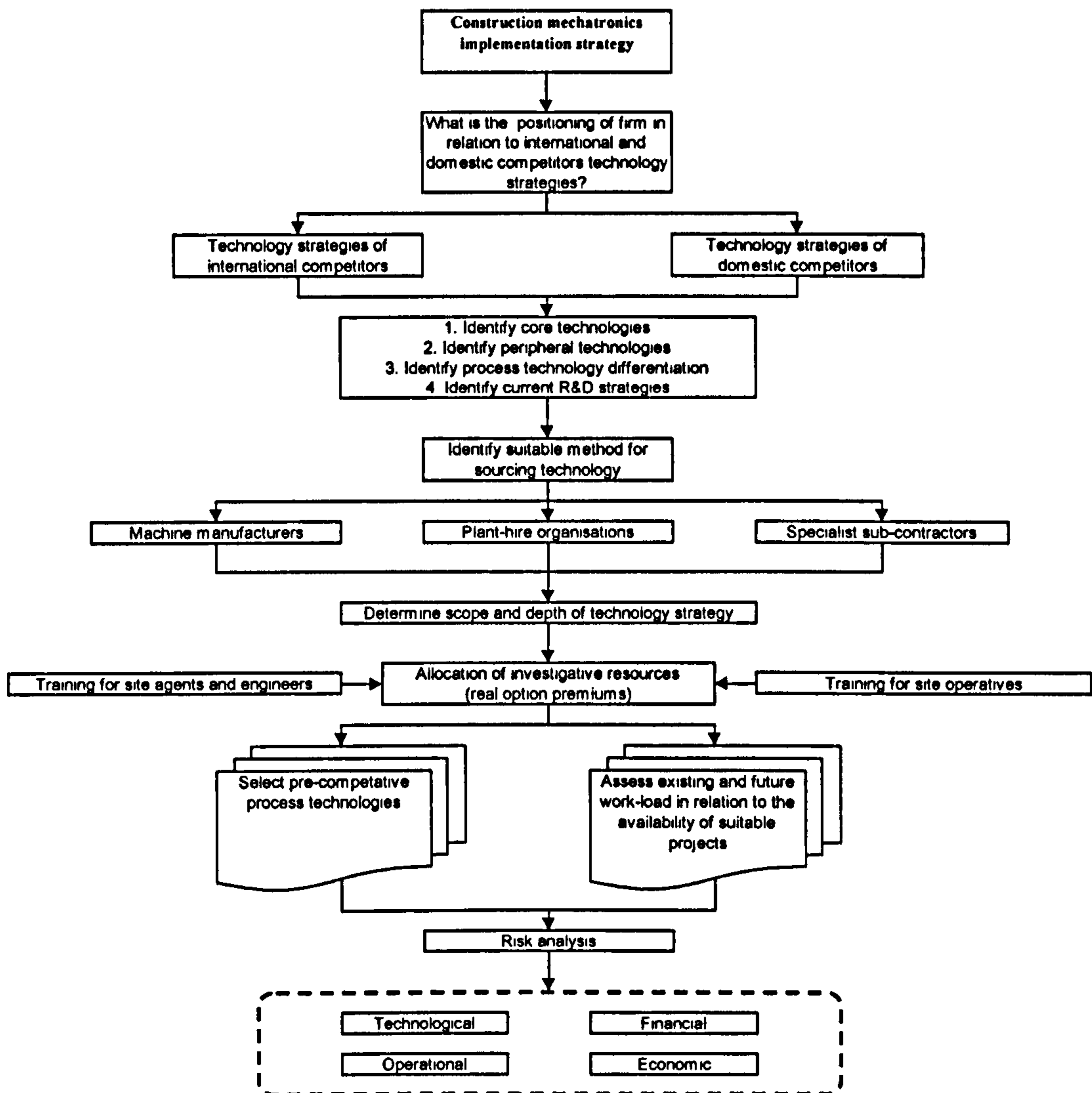


Figure 6.6: Mechatronics strategic decision, implementation and evaluation process

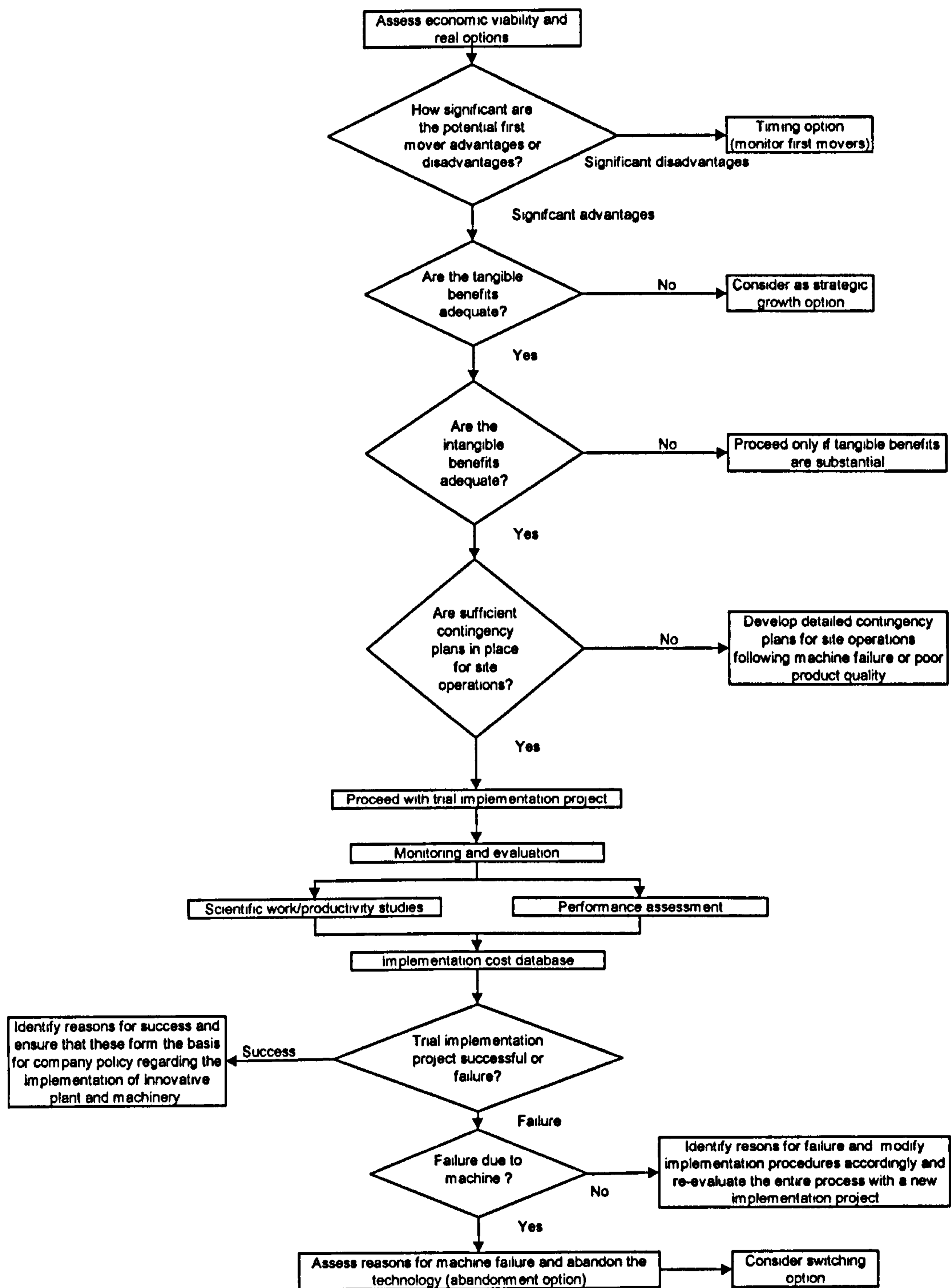


Figure 6.6 (cont.): Mechatronics strategic decision, implementation and evaluation process

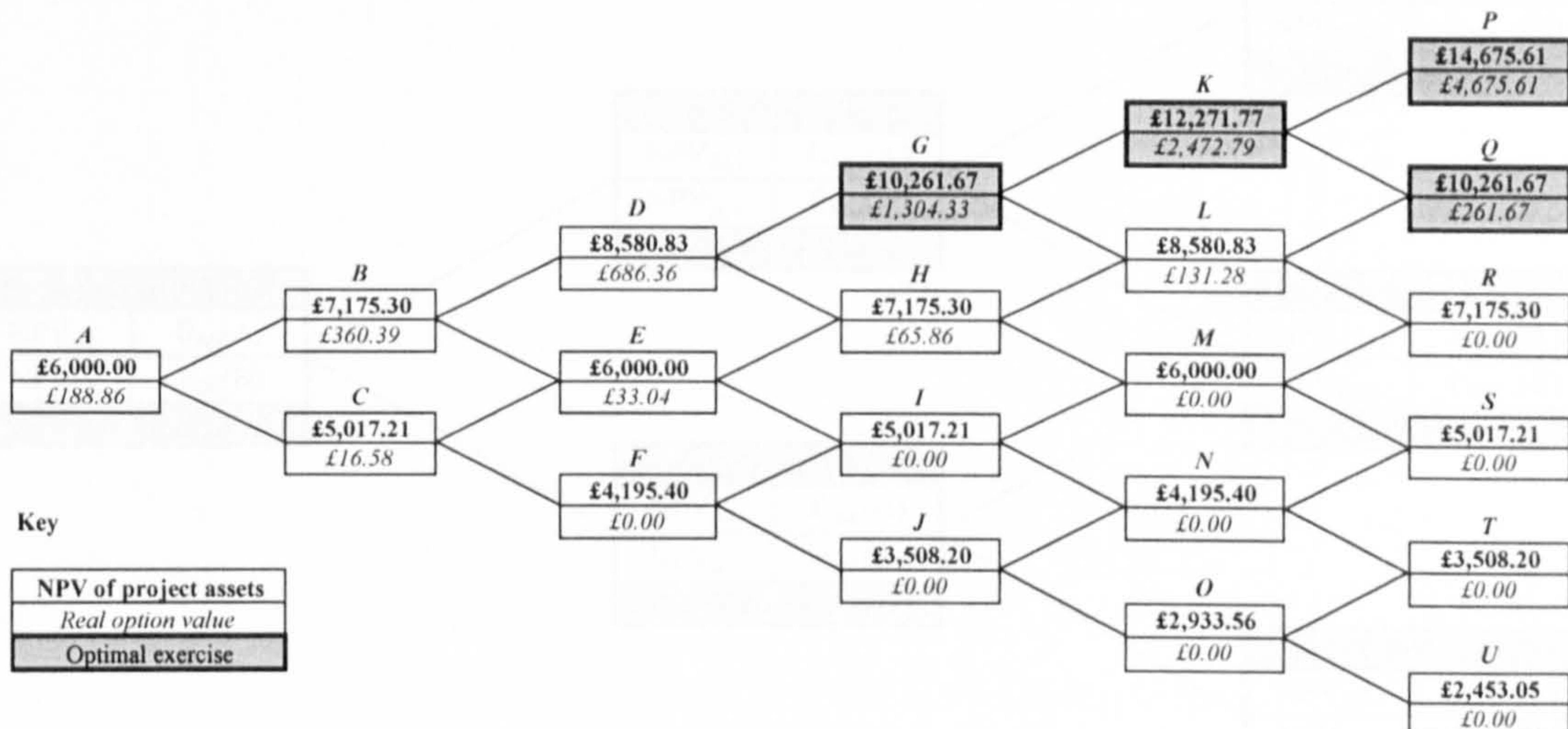


Figure 6.7: Five-step timing option binomial tree (American call)

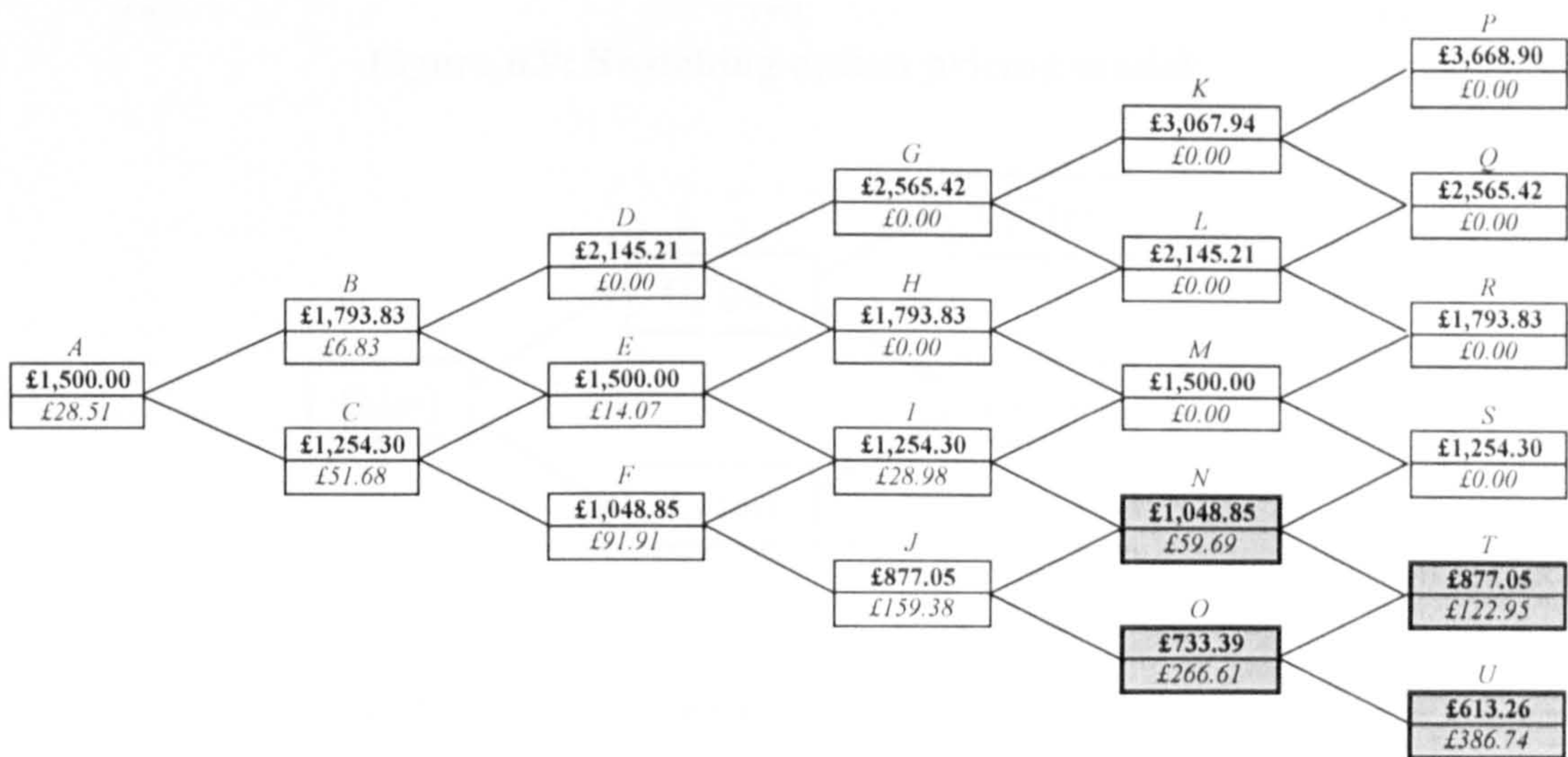


Figure 6.8: Five-step abandonment option binomial tree (American put)

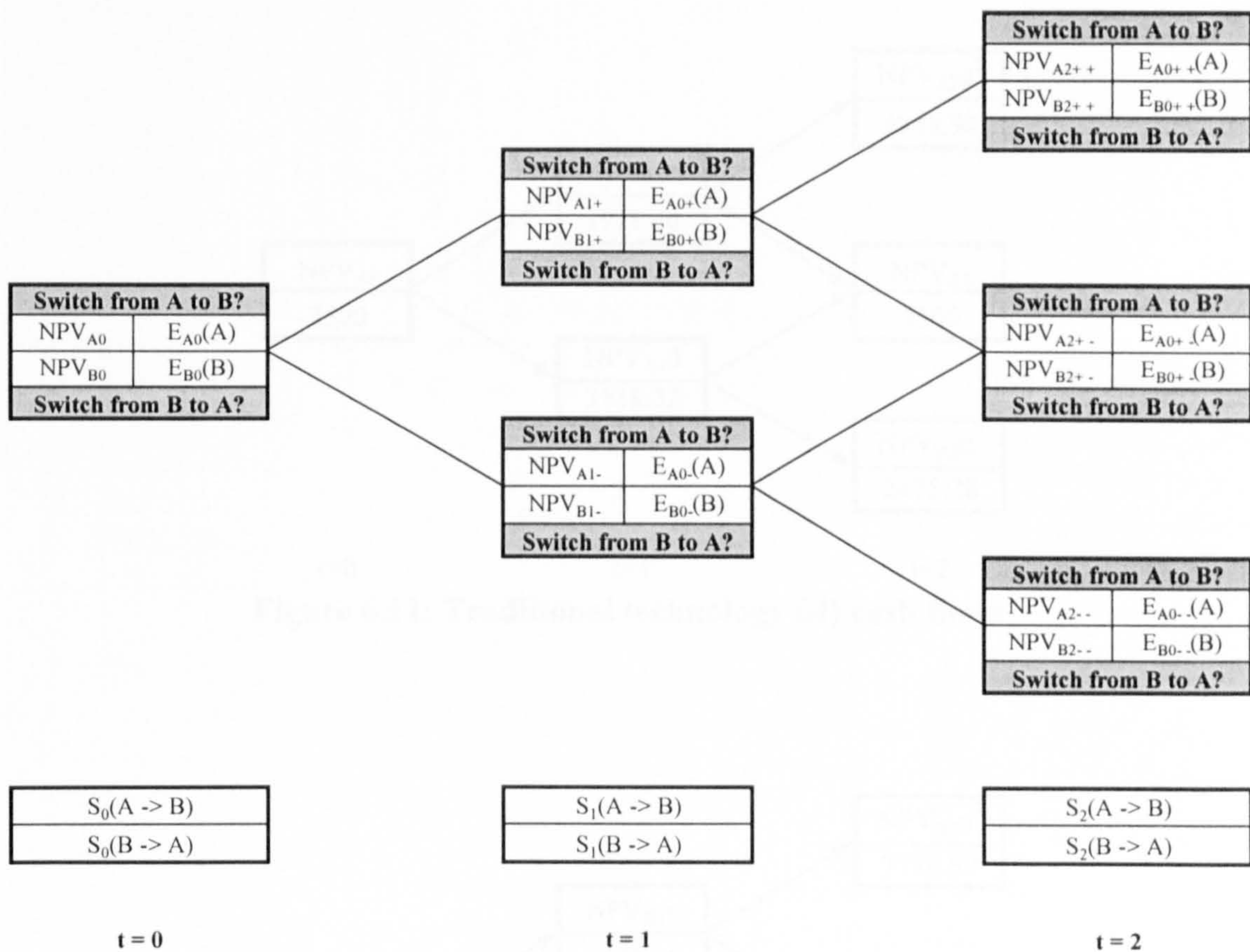


Figure 6.9: Switching option pricing model

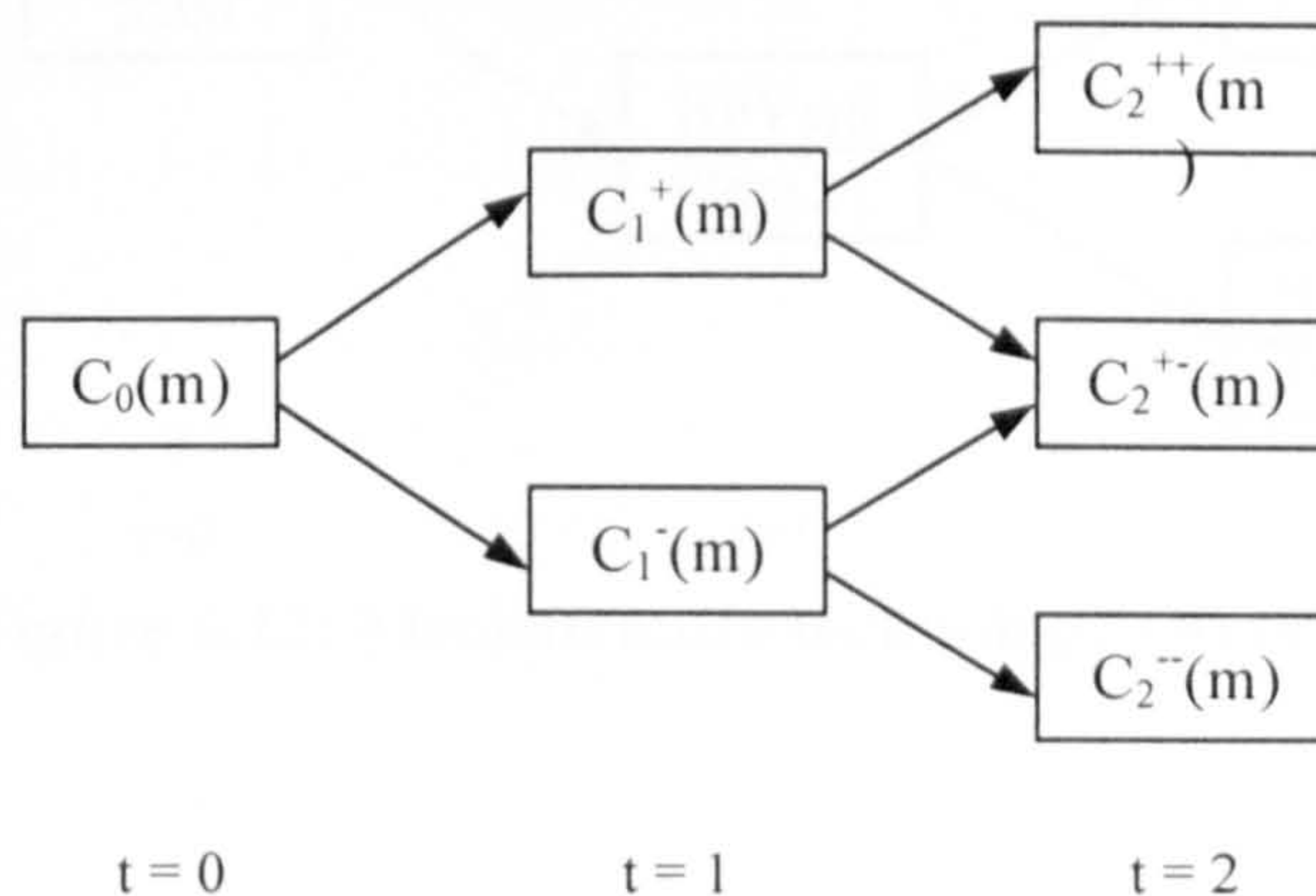


Figure 6.10: Switching option cash flow generated in time period, t , in state, s
Source: adapted from Trigeorgis 1996

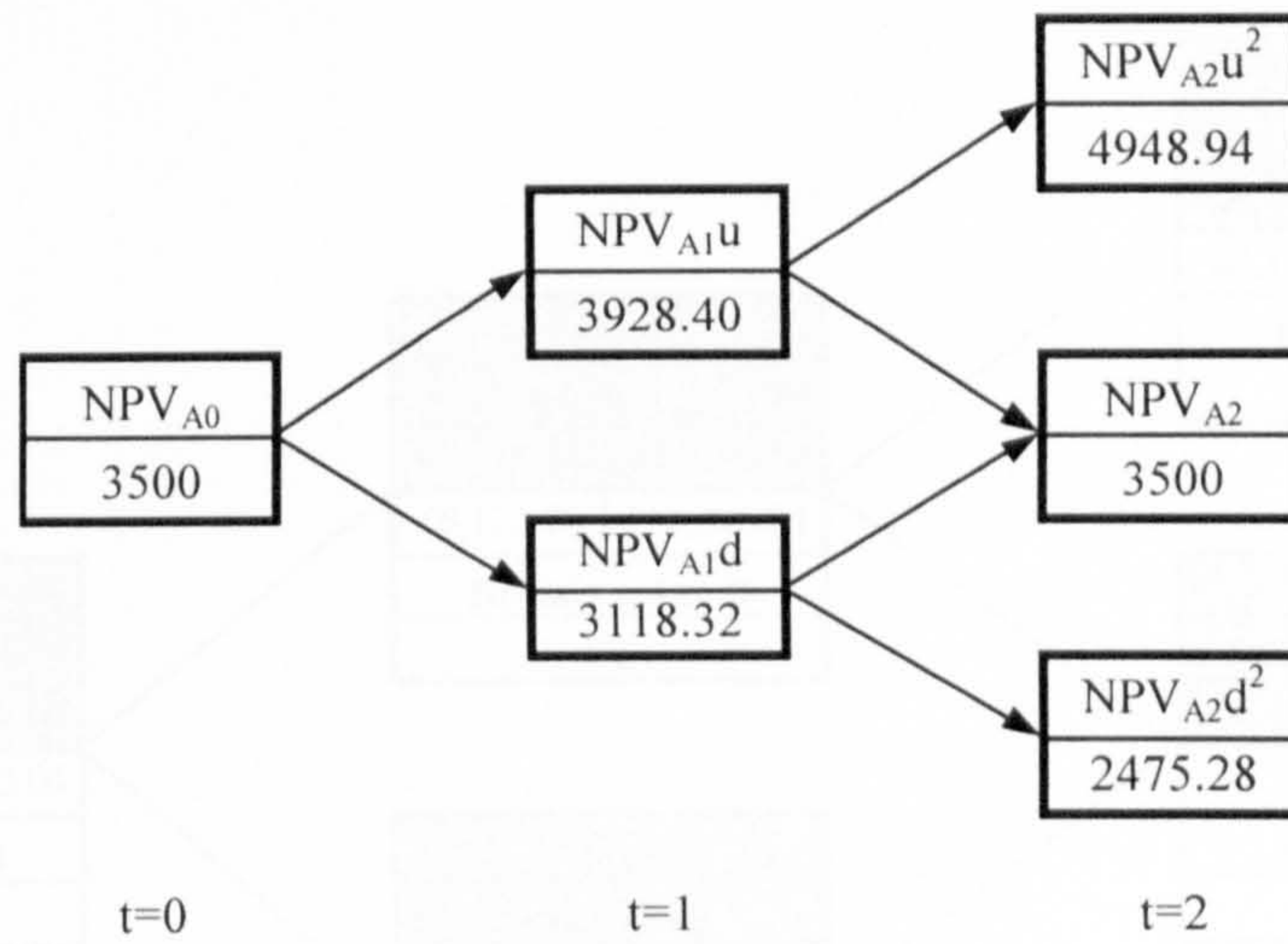


Figure 6.11: Traditional technology (A) cash flows

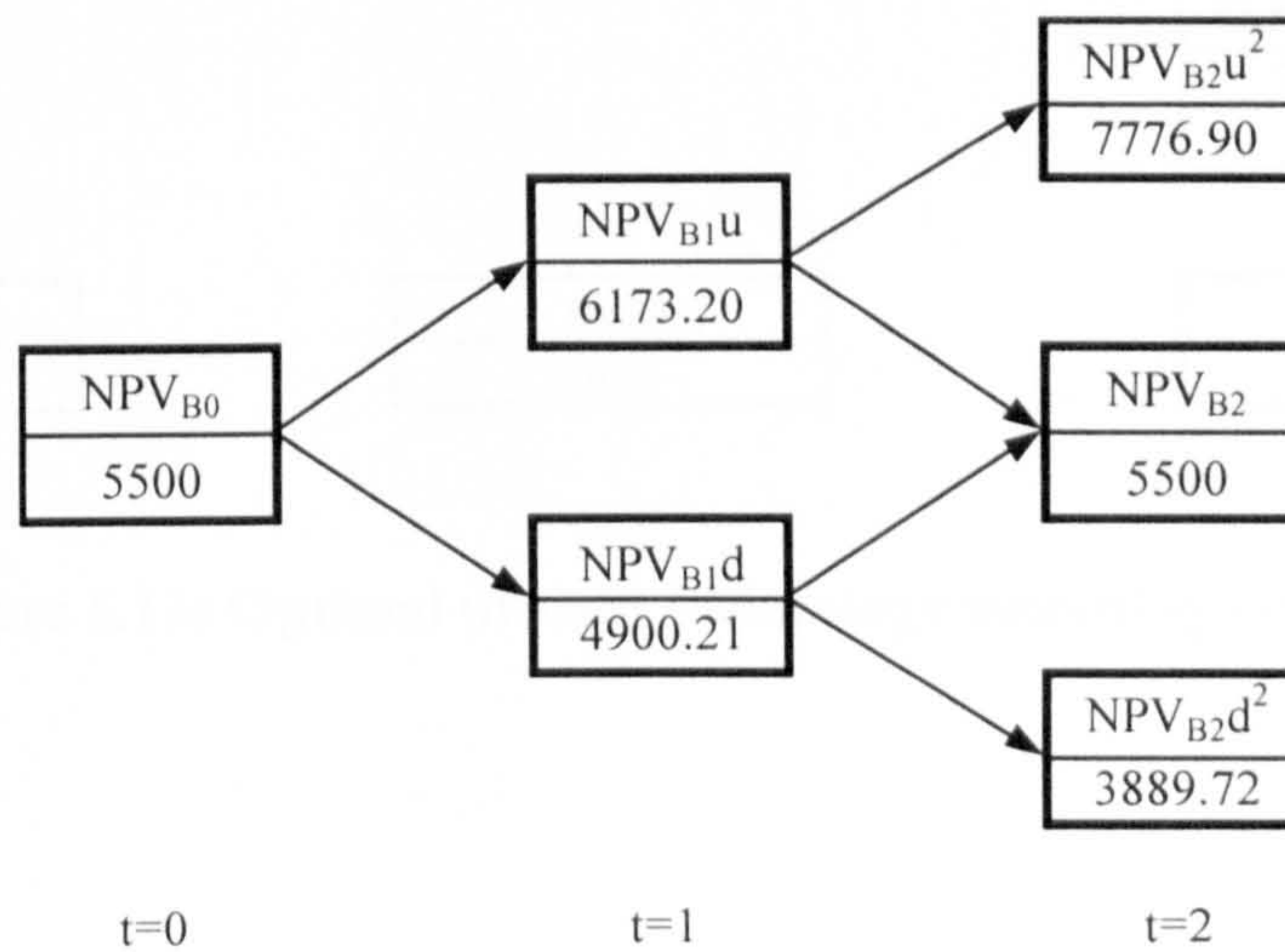


Figure 6.12: Mechatronics technology (B) cash flows

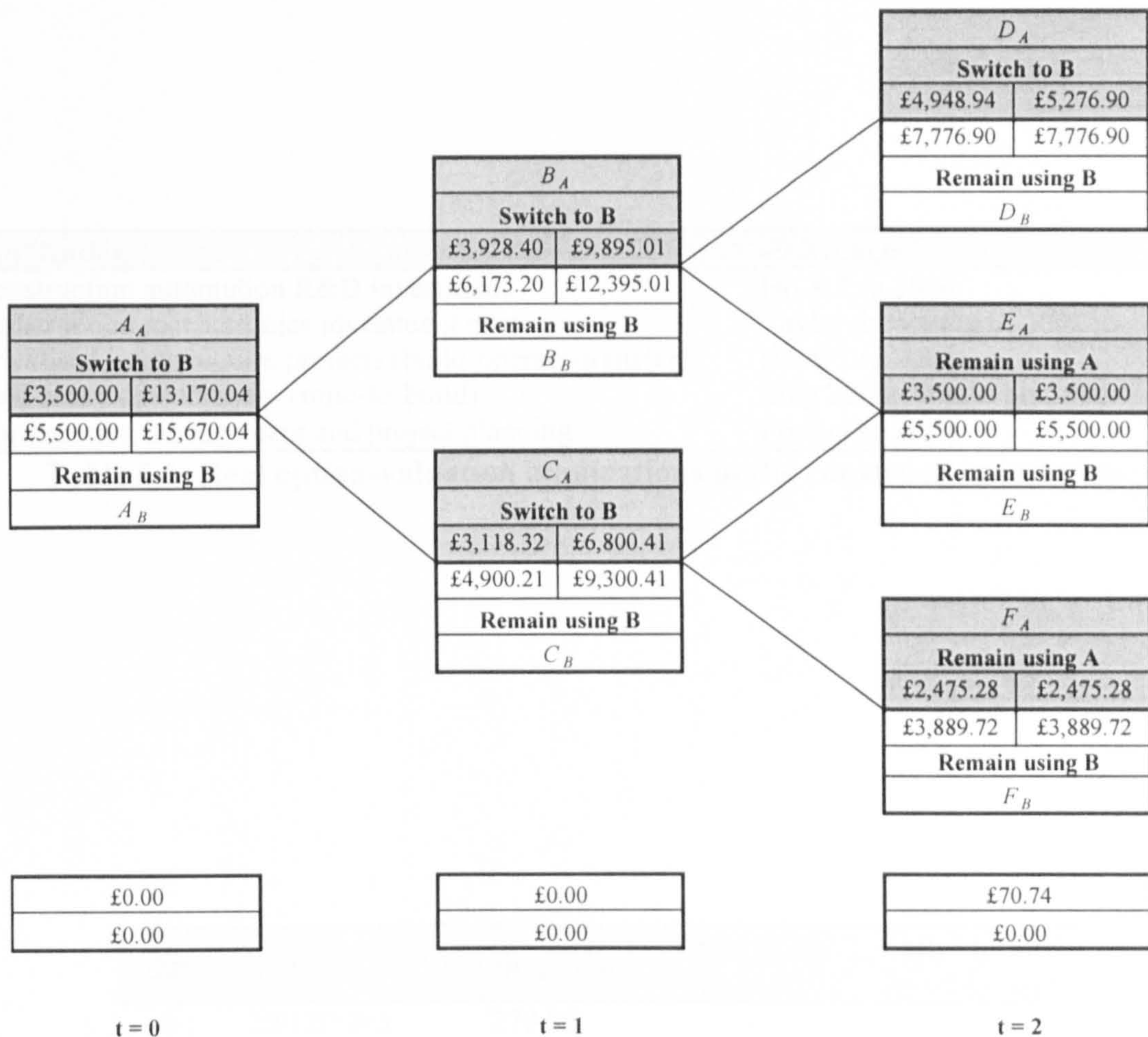


Figure 6.13: Optimal process technology switching options

Application	References
Construction automation R&D investment	Ho & Liu 2000
Construction mechatronics investment strategies	Taylor & Wamuziri 2002
Privatised infrastructure projects (build-operate-transfer)	Ho & Liu 2002
Real estate development (time-to-build)	Sing 2002; Trigoergis 1996
Construction management and project planning	Ford <i>et al</i> 2002

Table 6.1: Real option-valuation applications in the construction industry

Day	Date	Closing Price	Price Ratio (A_t/A_{t-1})	Daily Return $u_t = \ln(A_t/A_{t-1})$
0	20/12/1995	270.86	-	-
1	21/12/1995	266.94	0.9855	-0.0145
2	22/12/1995	268.90	1.0073	0.0073
-	-	-	-	-
1258	16/10/2000	110.50	0.9955	-0.0045
1259	17/10/2000	110.50	1.0000	0.0000
1260	18/10/2000	112.00	1.0135	0.0134
<i>Standard deviation</i>				<i>0.0262</i>
<i>Volatility</i>				<i>0.4161</i>

Table 6.3: Estimation of volatility from historical market data

Volatility Type	Description	Data Acquisition Example	Source
Historical			
Industrial sector	Average annual volatility of a particular industrial sector.	Historical volatility of FTSE Construction and Building Materials sector.	Amram & Kulatilaka 1999a
Company's equity	Average volatility of investing firms equity or firms within comparable operating risk category.	Historical volatility of investing companies equity or firms undertaking similar operations.	Anderson 2000; Ho & Liu 2000
Commodity	Volatility of cash flows for an oil refinery plant project.	Call options on crude oil contracts.	Amram & Kulatilaka 1999b; Trigeorgis 1993
Implied	Using current prices for traded options within similar industrial category, an iterative search process may be used to determine the implied volatility from the current market price and the B&S formula.	Option values for crude oil call options may be used to determine the implied volatility of a refinery plant investment opportunity.	Luehrman 1998
Estimate			
Subjective managerial estimates	Subjective managerial estimates used when historical data is unavailable.	Elicit estimates of investment volatility from senior management.	Ho & Liu 2002; Copeland & Antikarov 2001
Sensitivity analyses	Estimated at 20% (as a base case), and for sensitivity purposes it is varied between 10% and 30% annually.	A range of volatility values are adopted and their effect upon the value of the real option is examined.	Kemna 1993
Off-line simulation	Develop a detailed plan for the tasks to be conducted by the automated plant. The task plant includes schedules, safety procedures and costs estimates. These may then be used to provide estimates for the uncertainty surrounding the investment cash flows.	Use PC based off-line simulation package to determine the automated systems cost parameters and calculate the ownership and operating costs per operating hour. Uncertainty regarding specific costs may indicate their potential volatility and assist managerial estimates.	Seward <i>et al</i> 2001; Warzawski 1999; Jansson 1994
Simulation	Synthesise a probability distribution for project returns using Monte Carlo simulation and determine the standard deviation of investment returns.	Input variables for financial risk analysis include: site-set-up costs, consumable resources, operators pay, maintenance and rate of utilisation	Copeland & Antikarov 2001; Taylor <i>et al</i> 2000; Benaroch & Kauffman 1999; Luehrman 1998; Mann <i>et al</i> 1992

Table 6.2: Summary of volatility estimation techniques and data sources

System Concept	Japanese General Contractor										
	Kajima	Toda	Hazama	Fujita	Obayashi	Shimizu	Taisei	Takanaka	Kumagai	Maeda	Tokyu
Earth working	X			X			X				X
Foundation work	X				X		X				X
Crane work				X	X	X					
Dam construction	X		X	X	X	X			X		
Concrete distribution and finishing	X		X	X	X	X	X		X		X
Mountain tunnelling		X	X	X	X		X		X		
Shield tunnelling	X	X	X		X	X					
Marine work	X						X				
On-site welding	X			X		X	X		X		
Automated building construction (CIC)	X			X	X	X	X		X		
Finishing work	X	X	X	X	X	X	X		X		
Material handling and manipulation	X			X	X	X	X		X		X
Surveying	X						X				X
Inspection and monitoring	X		X		X		X		X		X
Maintenance	X				X	X	X		X		X

Table 6.4: Technology strategies of Japanese general construction contractors

Source: Cousineau & Miura 1998; Japanese Council for Construction Robot Research 1999 and corporate brochures

Option parameters	Value
S_0	£6,000
X	£10,000
r	0.065
σ	0.40
t	1.00
Δt	0.20
u	1.20
d	0.84
a	1.01
p	0.49
$(1-p)$	0.51

Table 6.5: Timing option parameters

Option parameters	Value
S_0	£1,500.00
X	£1,000.00
r	0.065
σ	0.40
t	1.00
Δt	0.20
u	1.20
d	0.84
a	1.01
p	0.49
$(1-p)$	0.51

Table 6.6: Abandonment option parameters

Option Parameters	Value
S	£250000
S^*	£145403.23
σ	0.4
X_1	£50000
X_2	£150000
r	0.055
T_1	1
T_2	5
d_1	1.185
$N_1(d_1)$	0.882
d_2	0.385
$N_1(d_2)$	0.650
a_1	1.692
a_2	1.292
b_1	1.265
b_2	0.371
ρ	0.447
$N_2(a_1, b_1; \rho)$	0.918
$N_2(a_2, b_2; \rho)$	0.748
$N_1(a_2)$	0.902
$C(S, t)$	£89422.29

Table 6.7: Growth option valuation model parameters

Notation	Description
a	Growth factor
σ	Investment volatility
Δt	Incremental time period
u	Upward step size
d	Downward step size
p	Risk-neutral probability of upward NPV movement
$(1-p)$	Risk-neutral probability of downward NPV movement
r	Risk-free rate of return (3 month treasury bills)
$I(A \rightarrow B)$	Cost of switching from technology A to B
$I(B \rightarrow A)$	Cost of switching from technology B to A
$F(A \rightarrow B)$	Value of flexibility to switch from mode of operation A to B
$F(B \rightarrow A)$	Value of flexibility to switch from mode of operation B to A
$NPV_t^s(A)$	Net cash flow generated in year t in state s when using technology A
$NPV_t^s(B)$	Net cash flow generated in year t in state s when using technology B
$C_t^s(A \rightarrow B)$	Incremental (additional) cash payoff from voluntarily switching from technology A to B
$C_t^s(B \rightarrow A)$	Incremental (additional) cash payoff from voluntarily switching from technology B to A
$S_0(A \rightarrow B)$	Option to switch from A to B immediately
$S_1(A \rightarrow B)$	Option to switch from A to B in time period $t = 1$
$S_2(A \rightarrow B)$	Option to switch from A to B in time period $t = 2$
$S_0(B \rightarrow A)$	Option to switch from B to A immediately.
$S_1(B \rightarrow A)$	Option to switch from B to A in time period $t = 1$
$S_2(B \rightarrow A)$	Option to switch from B to A in time period $t = 2$
$E_t^s(A)$	Value of investment flexibility in time t (and state s) assuming technology A and optimal future technology switching
$E_t^s(B)$	Value of investment flexibility in time t (and state s) assuming technology B and optimal future technology switching

Table 6.8: Switching option parameters

Switching option parameters	Base case value
a	1.0054
σ	0.4
Δt	0.0833
u	1.1224
d	0.8909
p	0.4946
$(1-p)$	0.5054
r	0.065
$I(A \rightarrow B)$	£2500
$I(B \rightarrow A)$	£1000
$NPV_0(A)$	£3500
$NPV_0(B)$	£5500

Table 6.9: Hypothetical switching option parameters

Technology A (traditional plant and machinery)				
Time period	Net present value	Switching option value	Value of flexibility	Optimal mode
t	NPV_A	$S_{0,1,2}(A \rightarrow B)$	$E_t^s(A)$	$m_t^s(A \text{ or } B)$
0	£3500.00	0	£13,170.04	$m_0(B)$
I^+	£3928.40	0	£9,895.01	$m_1^+(B)$
I^-	£3118.32	0	£6,800.41	$m_1^-(B)$
2^{++}	£4948.94	0	£5,276.90	$m_2^{++}(B)$
2^{+-}	£3500.00	£70.74	£3,500.00	$m_2^{+-}(A)$
2^{--}	£2475.28	0	£2,475.28	$m_2^{--}(A)$
Technology B (mechatronics technology)				
Time period	Net present value	Switching option value	Value of flexibility	Optimal mode
t	NPV_B	$S_{0,1,2}(B \rightarrow A)$	$E_t^s(B)$	$m_t^s(B \text{ or } A)$
0	£5500.00	0	£15,670.04	$m_0(B)$
I^+	£6173.20	0	£12,395.01	$m_1^+(B)$
I^-	£4900.21	0	£9,300.41	$m_1^-(B)$
2^{++}	£7776.90	0	£7,776.90	$m_2^{++}(B)$
2^{+-}	£5500.00	0	£5,500.00	$m_2^{+-}(B)$
2^{--}	£3889.72	0	£3,889.72	$m_2^{--}(B)$

Table 6.10: Switching option value parameters and optimal switching decisions

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions of the study

This thesis has developed original work in the field of construction automation valuation and presents implementation strategies for the UK construction sector. The components claimed to be novel are, in particular, the critical examination of the state-of-the-art technology, the financial risk analyses, the application of real option-pricing theory to construction automation investment opportunities and the formulation of implementation strategies for UK plant hire firms and construction contractors.

This chapter presents general conclusions followed by specific conclusions arising from each strand of the research. Suggested areas for investigation are presented and discussed.

7.2 Specific conclusions: technology observation

A succinct and qualitative review of existing technological capabilities and future research directions was presented in Chapter 3 of this thesis. The following conclusions were drawn from the observation of the state-of-the-art technology.

1. Japanese contractors have significantly reduced their construction automation and robotics research programmes with regards to investment and allocation of research staff.

2. Japanese general contractors are not realising the tangible benefits perceived during the construction automation R&D programmes initiated from the early 1980's.
3. The use of fully autonomous single-task construction process technology is proving to be inherently complex and prohibitively expensive. Therefore, man-machine technologies are proving to be more successful in mechanising construction site operations.
4. The development of integrated automated construction systems (e.g., ABCS, SMART, MCCS, T-Up etc) has proven to provide an operational environment more suited to the operations of automated material process technologies. However, their complexity has been reduced in order to increase their economic viability and ease of application.
5. Ongoing Japanese research aims to further the development of multi-task technologies and computer integrated construction systems, which incorporate automated off-site pre-fabrication with construction erection systems.
6. Japanese contractors are primarily concerned with operational safety, improving the construction project environment and the strategic value of learning. Importantly, Japanese contractors are aware of their strategic competitive advantage with regards to their previous experiences with the deployment, operation and maintenance of automated construction process technologies.
7. There is a considerable range of tele-operated construction plant being utilised on UK construction projects. However, there has been minimal use of automated technologies on operational construction projects. Further research is required in order to gain

greater understanding of the innovative plant and machinery currently being utilised on UK construction and civil engineering projects.

8. Civil engineering operations involving heavy, hazardous and onerous work conditions provide opportunities for the deployment of automation and robotics. The nature of the materials (generally heavy, oversized and expensive) utilised generates a demand for material conveyance and positioning systems, which can eliminate health and safety hazards and provide improvements in site productivity.
9. Single-task automated construction technology has not provided the anticipated labour reductions and increased site productivity due their complex operational requirements and their inability to provide high rates of utilisation through a lack of industry demand.
10. Rather than developing construction automation systems specifically for their tasks, the use of off-the-shelf manipulators and standard components may provide a more economical solution to the development of automation and robotics systems for the construction industry.
11. The combination of off-site industrialised prefabrication and integrated automated construction provides significant economies in high-rise construction. Furthermore, the development of more sophisticated automated construction erection and interior finishing systems may provide even greater site productivity and labour reductions than presently experienced.
12. Japanese construction contractors have imitated and emulated each other's construction automation research and development strategies. Technologies are apparently

developed, firstly, in order to display technological prowess and, secondly, to provide competitive advantages. However, Japanese general contractors are successfully managing to deploy automation and robotics within operational construction environments.

13. The successfully applied automated systems presented within this Chapter are primarily providing increased site operative safety with secondary tangible benefits including increased productivity and quality.

7.3 Specific conclusions: economic appraisal

A review of construction automation economic valuation models was presented. A valuation model was presented, which segregated the complex costs and benefits associated with the research, development and implementation of automated construction. Furthermore, the economic significance of construction and machinery plant hire sector and their important role in the widespread use of innovative machinery was highlighted. The main conclusions drawn from the review of construction automation economics are given below:

1. For construction automation to be extensively used within the UK construction industry, scientific, technical and financial information must be disseminated among industry practitioners to provide specific and detailed information on the success of existing technologies.

2. Successful application of existing technologies requires construction managers to overcome the organisational, social and human barriers associated with the application of automation technology to construction operations.
3. Existing economic appraisal methodologies do not attribute the costs and benefits associated with construction automation investment opportunities to the relevant parties.
4. Considering the substantial private investment of the Big-Six Japanese construction contractors and their collaboration with experienced robot manufacturers (e.g. Hitachi, Mitsubishi, etc) it is understandable why they have been successful in researching and developing automated construction technology. Furthermore, there are serious demographic issues, which appear to have encouraged their development.
5. The implementation of automated construction technology will have effects beyond those directly replaced by the machines. Foremen, civil engineers, construction managers and organisational control structures are likely to be affected.
6. In order to provide the high utilisation rates justifying investment in automated construction technology, machines must be hired to construction contractors via specialist plant hire firms. Therefore, contractors will not be required to maintain and repair the systems. Furthermore, the machines will be utilised by a range of contractors and passed from one site to another to secure high rates of utilisation.

7.4 Specific conclusions: financial risk analysis

Monte Carlo simulation has been integrated within a DCF appraisal methodology for automated construction technology appraisal within the plant hire sector. Details of this study may be found in Chapter 6 of the thesis. The main conclusions derived from this study are given below:

1. Monte Carlo simulation has been successfully incorporated into a plant-hire appraisal model to perform probabilistic financial risk analysis for a hypothetical automated construction systems investment.
2. A total of 50000 iterations was shown to be sufficient for the probabilistic risk analysis model to achieve convergence.
3. The derivation of objective input parameter distributions using historical data is essential for refining and validating the generic financial risk analysis model presented for automated construction systems.
4. Historical mechatronics maintenance data is required to determine the maintenance characteristics of the existing technologies.
5. For the subjectively assessed parameters used in the present research, the normal, triangular, uniform and discrete distribution functions provide similar predictions for investment NPV risk. However, the uniform distribution overestimates the probability of extreme values and, subsequently, provides over conservative results.

6. The simulation results are dependant upon the shape of the input distribution, the manner of setting the mean and standard deviation and the correlation between each input parameter. However, the choice of distribution type is insignificant in relation to the subjective estimation of input parameter variables.
7. The upper limits for hourly hire rates must be set in relation to the task undertaken by the machine and the total hourly cost of the task using traditional techniques and human operatives.
8. Automated construction systems investment is sensitive to the rate of interest, the residual value of the machine, maintenance costs and the growth in maintenance costs as the machine nears to end of it's functional life.
9. Cheap sources of finance must be made available to investors in automated systems in order to stimulate further R&D, investment and widespread adoption of innovative construction plant and machinery.

7.5 Specific conclusions: real option valuation

Real option valuation methodologies have been applied to the strategic valuation of construction automation investment. Details of this study can be found in Chapter 7 of the this thesis. This study was important as it provided a means of assessing the true strategic value of automation investment. The real option valuation models presented do not claim to replace managerial intuition, however, they provide a quantitative assessment of investment flexibility. This study has provided an insight into the limitations with existing

DCF appraisal methodologies, which are presently used to value construction automation investment. The following main conclusions were drawn from this study:

1. Construction automation investment opportunities may be undervalued using traditional DCF appraisal techniques alone.
2. Real option valuation compliments NPV analysis when assessing the strategic value of construction automation investment opportunities. Real option valuation considers investment flexibilities, which are neglected using DCF appraisal methodologies.
3. Real option valuation techniques provide quantitative analysis of construction automation investment flexibility. They aid the assessment of strategic investment opportunities and add financial insight to the valuation of possible strategies.
4. Real option valuation methodologies have been successfully adapted for the valuation of strategic automated construction technology investments.
5. The B&S and binomial option valuation models can be used to provide an approximation of the value of strategic construction automation investments.
6. Abandonment options provide a means of valuing possible exit scenarios further to implementation failure or insufficient market demand.
7. Timing options successfully incorporate managerial patience in exercising automated technology investment options. They provide a means of valuing investment deferral and the possibility of pre-competitive investment.

8. Growth options integrate the valuation of automated technology investments and strategic planning.
9. Switching options may be used to value construction process flexibility. Namely, the possibility of switching between traditional plant and automated technologies.
10. Switching options may be used to value contingency planning, in the sense that the objective of such planning is to understand the available alternatives following implementation failure.
11. The cost comparison between mechanised and manual operations may only be undertaken further to pioneer implementation ventures, which will scientifically determine the true operating and ownership cost of the selected innovative technology. Further to obtaining this information, the operating switching options may be valued and the decision regarding the optimal plant and machinery may be undertaken.
12. Despite the limitations of real option valuation, the models presented within this Chapter provide quantitative procedures for the amalgamation of technology investment and technology strategies. Furthermore, the methodologies may be used to provide construction industry professionals with indications of where to focus their efforts in order to maximise the value of their construction automation investment options.

7.6 Final remarks

The findings of this research, as summarised above, have led to a better understanding, both quantitatively and strategically, of the pertinent issues relating to the valuation and strategic implementation of automated construction technology. There has been a distinct leap forward in the understanding of the automated technology, which may be appropriate for construction projects. Despite the development of a broad range of single task systems, future development is concerned with the application of multi-task systems and integrated computer controlled construction systems. There have been considerable successes with existing automated construction systems and they continue to be refined and streamlined in order to increase productivity and reduce costs. It seems that the strategic value of investment strategies has been neglected from applying DCF appraisal techniques when considering technology strategies. The author has presented valuation models, which examine and value a selection of the investment flexibility options that are neglected using DCF methodologies alone.

The present study has raised many questions concerning the continuing research, development and widespread introduction of automation and robotics in the construction industry. The following sections present a selection of recommendations for future work.

7.7 Recommendations for future research: introduction

Recommendations for future research are outlined within this section to assist the continuation of the research presented in this thesis and to connect it with future research projects within the field of construction mechatronics. The recommendations are not claimed to be any less important than the work already carried out by the author. However,

the recommendations do represent distinct steps forward from the authors current findings and form potentially years' worth of future research.

7.7.1 Scientific work studies

Technology demonstration projects will incorporate productivity studies comparing automated construction technology with traditional manual construction processes. With support from machine manufacturers, specialist sub-contractors and UK construction contractors, a selection of commercially available systems will be evaluated on selected UK construction projects. The efficiency of the machines will be evaluated and benchmarked, using key performance indicators, against traditional construction techniques.

The following objectives will be pursued in an integrated theoretical and experimental study:

- the valuation and selection of mechatronics technology for transfer into UK construction and civil engineering operations; and
- the *in-situ* analysis of the selected machines to facilitate work measurement and efficiency studies.

Scientific work analyses involving method studies and work measurement will be implemented to evaluate the productivity, safety and quality improvements yielded from selected pre-competitive machines. Work measurement will facilitate improved planning and scheduling, greater control of implementation costs and the production of a cost data base for estimating the value of future application and predicting the potential value of prototype systems.

Activity sampling will be effective in determining on-site operational inefficiencies, which may reduce the overall productivity of the selected machines. These studies will provide data regarding the utilisation of the machine and the various proportions of time that the operators are occupied by specific activities. Productivity ratings will be used to highlight inefficiencies in operation and support activities by classifying the effectiveness (in a production sense) of the work being carried out.

Time studies will record times and rates of working for manual compared to automated procedures. Analysis of the data will provide standard times and standard production outputs for executing automated activities at defined levels of performance. Method studies may incorporate the systematic recording and subsequent examination of working methods in order to facilitate improvement. Process charts will provide diagrammatic records of the sequence of activities involved in the automated construction processes. They will assist in the visualisation of the processes and the explanation of the sequence of activities in the operation of the selected machines. Specifically, process charts will assist in the establishment of economically efficient operations. These may reduce material wastage, reduce idle times, smooth the flow of materials, eliminate unnecessary movements by improved layout, improve the quality of production and reduce the future cost of implementing similar technology. Through analysing the results of the method studies, improved or new working methods may be revealed.

Project cash flow data will be recorded to facilitate financial analyses of the implementation studies. A historical database of implementation expenditure may assist in the future appraisal of mechatronics technology. The results of the research will be of immediate benefit to UK plant hire organisations and construction contractors considering

implementing mechatronics technology to improve the safety, quality and productivity of their future operations.

7.7.2 Construction of an implementation cost database

A substantial lack of objective data regarding set-up and implementation expenditures is evident within the existing literature. Furthermore, the author experienced significant difficulties in obtaining historical cost data, which was either unavailable or sensitive to the operations of the firm developing or implementing the technologies in question. An internet based implementation, repair and maintenance cost database requires development in order to assist contractors and plant-hire organisations in assessing the efficiency and cost effectiveness of the available construction mechatronics technology.

7.7.3 Real option valuation: a game theoretic approach

Further research is required in the combination of real option construction mechatronics valuation models and game theoretic models. Real option-pricing may be combined with the basic principles of game theory to explore various investment timing strategies in follow-up investment based upon the reaction of industry competitors under different market conditions. Real option valuation and game theory, in combination, may examine the maximisation of value with consideration of the strategic actions of other organisations within the sector. Emerging competition or rivalry may create an incentive to invest early, as postponement of the investment may result in value erosion.

7.8 Summary

The author has presented various recommendations for future research regarding the implementation and analysis of construction mechatronics. A selection of the recommendations are continuations of the author's work where it was either incomplete or could be explored further. However, some of the author's work such as the real option analysis models and implementation strategies are ready to be incorporated within construction industry technology planning activities.

Future research projects should aim to incorporate the author's findings into the valuation and implementation of construction mechatronics technology. This concludes the recommendations for future research and the thesis proper; a cited reference list and four appendices containing seminal research and publications derived from this thesis.

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APPENDIX A

Kulatilaka: financial, economic and strategic issues concerning the decision to invest in advanced automation

Kulatilaka (1984) highlighted the unique characteristics of automation investment opportunities and the need to modify conventional capital budgeting techniques to account for these. He identified the various economic effects and their expected cash flow streams, incorporated the risk characteristics of these cash flows into their respective discount rates and provided a brief analysis of the long term strategic implications of investment in flexible automated manufacturing systems.

The costs and benefits were identified as:

- *Initial purchase cost* – the final cost will exceed the initial purchase cost due to the cost of interfacing, rearrangement and necessary modifications to standard off-the-shelf systems. In addition, there is a need to re-train labour, to reschedule other parts of the plant and for the employment of specialised systems consultancy services. Furthermore, the product may need re-designing in order to facilitate automated manufacturing.
- *Operating costs* – a simplified depiction directly replaces labour with increased requirements for electrical energy, computer resources and skilled maintenance personnel. Operational savings (i.e., lower salaries, reduced over-time, pensions, insurance) must be closely compared to the increase in the number of technically qualified maintenance personnel required to operate the new automated systems.
- *Reliability* – increased reliability was sighted as a common advantage with the use of advanced manufacturing automation. Robots do not go on strike, nor require vacations and coffee breaks. In general, automated systems have higher up-time than conventional human operatives.
- *Product quality improvements* – the quality of output can be assured to be far more uniform than under manual operations. Quality improvements may be translated into lower rates of product quality rejection. Finally, the market effects due to a

reputation for increased reliability may contribute to the strategic position of the firm in comparison with its competitors.

Various strategic implications and long term ramifications were highlighted as contributing favourably towards the decision to install flexible manufacturing systems. These were concluded as forming the subjective component of the investment decision. Flexibility can provide an enhanced ability to adjust production volumes to handle unanticipated changes in demand. By having this capability, a firm can produce at a lower cost, provide a higher quality product and meet consumer demand with shorter waiting times. A firm with a lower level of adaptability and with high manual labour resources may take too long to adjust production following a period of recession, i.e. it may take longer to re-hire staff that to increase to the operating hours of the manufacturing robots.

The substitution of capital for human labour raises the proportion of fixed capital within the firm. Kulatilaka (1984) used the capital asset pricing model to show how the project's opportunity cost of capital is proportional to the ratio of present value of the fixed cost to the present value of the project. The proportionality constant is the beta (β) value of the project revenues. The relationship is expressed as follows:

$$\beta_{project} = \beta_{revenues} \left[1 + \frac{PV_{fixed}}{PV_{project}} \right] \quad A.1$$

The ratio of present values is high for capital intensive investments, such as manufacturing robots. Therefore, the beta value of such a project will be higher than that of the revenues alone. To determine the required rate of investment return, the following equation is used:

$$r_{project} = r_{risk-free} + \beta_{project} (r_{market} - r_{risk-free}) \quad A.2$$

Following the determination of the appropriate risk adjusted rate of return, a single formula for the incremental NPV of the investment can be constructed as follows:

$$\begin{aligned}
 NPV = & PC(0) + RP(0) + RDP(0) + IC(0) + RT(0) + OI(0) + \\
 & \sum_{t=0}^N [LS(t) + SL(t) + MS(t) + EC(t) + HL(t) + LI(t)] + \\
 & ITC(0) + \sum_{t=0}^D DTS(t)
 \end{aligned}
 \tag{A.3}$$

where:

- PC* = purchase cost of the machine and equipment;
- RP* = cost of rearranging the plant;
- RDP* = cost of redesigning the product;
- IC* = cost of interfacing;
- RT* = cost of retraining labour or hiring labour with new skills; and
- OI* incorporates any miscellaneous installation costs.

These are all incurred at time $t=0$.

Incurred over the economic life of the machine are:

- LS* = labour savings;
- SL* = increased cost of skilled labour;
- MS* = material savings;
- EC* = energy cost increase;
- HL* = heating and lighting cost change;
- LI* = lower inventory costs;
- ITC* = investment tax credits; and
- DTS* = depreciation tax shields¹.

The economic life of the machine is denoted by N and D is the depreciable life of the project.

¹ The role of taxes is critical in any financial valuation. However, this NPV calculation is based upon the American taxation system of 1983 and would be subject to variation if used within the UK.

Specific care must be taken to ensure that the labour savings generated by the use of an automated system are not counteracted with the need to employ a large pool of technically qualified personnel for servicing the automated manufacturing systems. These employees would certainly be paid higher than their predecessors and great care must be taken to ensure that the net labour cost is indeed reduced under the advanced automation.

Finally, this work provides an early indication of the strategic options available to manufacturing firms considering investment in flexible automated manufacturing systems. The possibility of installing an automated system and monitoring its performance provided useful information for future investment decisions concerning similar technology. Furthermore, decisions concerning the abandonment of the pioneer technology were considered following the information provided from earlier learning experiences.

Kaplan (1984) provided a discounted cash flow appraisal technique using a discount rate adjusted for the systematic (specific) risk of the investment project. The appraisal technique reduced managerial subjectivity and provided a theoretically justified method for incorporating financial risk within the discount rate. However, there are notable problems associated with the use of discrete discounted cash flow investment appraisal techniques. These techniques ignore the possibility of investment flexibility and the intangible value of certain investment opportunities.

APPENDIX B

Warszawski: economic implications of robotics in building

Warszawski presented a detailed outline of the costs and benefits, which must be considered within an economic assessment of the research, development and practical deployment of automation and robotics within the construction industry (Warszawski 1985; 1986). These costs were classified as follows:

- *Development costs* – expenses associated with labour, materials and facilities for researching, testing and evaluating the various alternative robotic solutions.
- *Investment costs* – includes depreciation and interest on investment. Parameters, which must be known for their assessment, are the purchase cost of the machine, its economic life and the salvage value at disposal.
- *Set-up costs* – include the installation of the machine at its workplace, the learning and programming expenses. These costs are mainly composed of the operator learning expenses.
- *Maintenance costs* – include regular inspection, maintenance and breakdown repairs.
- *Operation costs* – electricity (fuel) costs and the cost of transferring the machine from one location to another (intra and inter-site).
- *Indirect expenses* – include the adaptation of the work environment to suit the employment of the robot.

In conjunction with the costs outlined above, the following benefits may be realised:

- *Labour savings* – wages, fringe benefits and associated overheads are reduced due to direct replacement of site labour by robots.
- *Higher quality of product* – owing to greater precision, material wastage is reduced, less remedial repair work is required, maintenance expense over the economic life of

the structure are reduced and higher user satisfaction is generated through the increased performance of the finished structure.

- *Elimination or reduction of human involvement* – greater site safety is realised through displacing human operatives from hazardous tasks undertaken in hostile and harsh environments. This minimises injuries and any associated decrease in productivity and work stoppages.

The feasibility analyses presented by Warszawski were primarily concerned with the value of the construction robot to the user, i.e. the construction contractor utilising the machine on site. The value of the machine was defined as the highest price the user may be willing to pay for it while still retaining the economic advantage from its use. This value was then calculated as the present worth of the direct savings realised from the deployment of the robot minus the expenses incurred.

The value of a robot was then calculated from the following equation as the discounted net worth of service over the economic life of the machine:

$$V = (kL - M - O - T + rP) \frac{(1+i)^n - 1}{i(1+i)^n} \quad \text{B.1}$$

where:

- k = number of replaced operatives;
- L = saved labour cost per year per one replaced operative;
- M = cost of maintenance per year;
- O = cost of robots operation per year;
- T = cost of robots transfers per year;
- r = tax reduction rate (10-16%);
- P = initial capital investment;
- i = interest rate (7-10%); and
- n = economic life of robot (3-5 years).

The above valuation technique assumed that the real interest rate was between 7 and 10%, which corresponded to a market rate of 13 to 16% (inflation of 6% per annum). This ignores any variation in the cost of capital between the various sizes of firm operating within the construction industry. Specifically, it may be inappropriate to attribute research and development costs to the end user. Surely, these costs will be borne by the machine manufacturer. Furthermore, the attribution of maintenance and repair expenditure to the end user (the construction contractor) neglects the possibility of these expensive machines being deployed through the UK construction plant hire industry. Owing to the need for high utilisation rates and construction contractors having cyclical demand for specialised plant and machinery, it may be more appropriate for construction automation and robotics to be deployed through the plant hire sector. Warszawski (1985) concluded that the feasibility of construction robots will only be assured if the intensity of their employment, measured in working hours per year, is maximised.

APPENDIX C

Warszawski & Rosenfeld: feasibility analysis of robotised vs manual performance of interior finishing tasks

The Technion Autonomous Multipurpose Interior Robot (TAMIR) was an experimental prototype interior finishing system adapted from a General Motors Funac S-700 manufacturing manipulator. The manipulator was mounted on a mobile platform and had 6 degrees of freedom, a maximum reach of 1.62m a payload capacity of 300N. The machine can be guided using a remote control console (teach box) or follow a pre-programmed path. Further developments include adapting the system to enable sensory devices and control mechanisms to allow the system to interact with its operational environment. The TAMIR system was designed as a general purpose automated interior finishing manipulator suitable for:

- painting walls and ceilings;
- plastering walls and ceilings;
- tiling walls; and
- constructing walls and partitions.

The feasibility of implementing the TAMIR system was determined from a direct comparison of robotic versus manual performance of interior finishing tasks. Warszawski and Rosenfeld (1993; 1994) presented a quantitative assessment of the robots feasibility with respect to potential savings in human labour requirements, the reduction of human exposure to difficult and hazardous conditions and increased quality of workmanship.

$$C = \frac{P.pr(i, n) + C_m}{H} + C_o$$

C.1

where:

P = investment cost of robot;

$pr(i,n)$ = capital recovery factor;

i = rate of interest;

n = economic life of machine;

C_m = cost of repairs and maintenance per year (10% of P);

H = number of hours employed per annum; and

C_o = operating costs (including wearing parts).

The feasibility analysis of the TAMIR system compared the cost of conventional manual methods with automated procedures. The unit cost of automated work included:

- *initial cost* – the robot, its operator and other auxiliary labour;
- *differential cost in materials* – consideration of more expensive specialised materials required for automated procedures;
- *the cost of moving system between work-stations* – this depends upon the amount of movements required per unit work, the distance between stations and its speed of movement;
- *the cost of positioning the system* – this depends upon the time to set up the system per work unit, i.e. the complexity of the installation procedure;
- *the cost of transfers between different work areas* – this depends upon the number of intra-site and inter-site transfers per work unit; and
- *the installation cost of the system* – depends upon the transportation time to site, the set-up time and the cost of other resources involved in the transfer.

Warszawski and Rosenfeld concluded that the major parameters in determining the unit cost of automated versus manual construction work can be separated into three distinct categories. These were:

1. *robot system* – its initial purchase cost, the total area it can cover from one workstation, its speed of movement and the extent of human control required;
2. *nature of construction site* – the nature of the tasks to be performed, their quantity, the number of intra-site transfers between work stations and the distribution of these work stations throughout the site; and
3. *task dependent parameters* – the output per hour for each task, the materials and auxiliary works required.

The interior finishing tasks selected for automation were executed effectively under laboratory conditions. Although it is technologically possible to have the TAMIR system autonomously navigate and propel itself to the next workstation, it was more advantageous to monitor the system during operation and have the operator guide the system to the next workstation. Warszawski and Rosenfeld concluded that increasing the number of systems that are under supervision could increase the productivity of the machine operators and reduce their requirement. Furthermore, from their feasibility analyses, the interior finishing system (TAMIR) had considerable potential for productivity improvements in painting, tiling, plastering and the construction of partitions and walls.

APPENDIX D

Published papers

The following published papers were derived from the work in this thesis. A set of these papers is bound with the thesis and may be found on the following pages. Full permission from the relevant publisher or copyright holder has been obtained. The pagination makes no attempt to follow that of the thesis proper; the numbering sequence follows that of the relevant parent journal or conference proceedings as appropriate.

1. TAYLOR, M.D., WAMUZIRI, S.C. & SMITH, I.G.N. (2003) Automated Construction in Japan, *Proceedings of the Institution of Civil Engineers, Civil Engineering*, 156 (1), 34-41, ISSN 0965 089 X.
2. TAYLOR, M.D. & WAMUZIRI, S.C. (2002) Strategic construction mechatronics valuation: a real option-pricing approach, *Journal of Financial Management of Property and Construction*, 7 (2), 75-90, ISSN 1366-4387.
3. TAYLOR, M.D., WAMUZIRI, S.C. & SMITH, I.G.N. (2001) Strategic mechatronics investment: understanding the managerial options, *Proceedings of the 17th Annual Conference of the Association of Researchers in Construction Management*, September 5th – 7th, University of Salford, Manchester, 333-342.
4. TAYLOR, M.D., WAMUZIRI, S.C. & SMITH, I.G.N. (2000) Analysis of risk in construction automation investment, *Proceedings of the 17th International Symposium on Automation and Robotics in Construction*, September 18th - 20th, Taipei, Taiwan, 109-114.