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THE RELATIONSHIP BETWEEN INFORMATION TECHNOLOGY AND CONSTRUCTION PRODUCTIVITY

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ABSTRACT OF DISSERTATION

Dong Zhai

College of Engineering

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ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By
Dong Zhai

Lexington, Kentucky

Director: Dr. Paul M. Goodrum, P.E., Associate Professor of Civil Engineering

Lexington, Kentucky

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ABSTRACT OF DISSERTATION

THE RELATIONSHIP BETWEEN INFORMATION TECHNOLOGY AND CONSTRUCTION PRODUCTIVITY

Over the past decades, information technology has been impacting industries, economics, the way of life and even the culture throughout the world. Productivity has been attracting much attention as an important indicator of economics, and numerous researchers have investigated the relationship between information technology and productivity. Construction is one of the largest industries in the United States, but little research has been conducted to investigate the relationship between information technology and construction productivity.

The major objective of this dissertation is to determine the degree (if any) to which information technology usage, specifically the use of information technology to automate and integrate construction project work functions, is related to construction productivity. First, the author analyzed the relationship between information technology and construction productivity on a national-level basis. Second, the author compared the relationship between information technology' contribution to value added growth and productivity in the construction industry with other industries. Third, the author performed a series of statistical analyses to investigate the relationship between construction productivity and automation and integration applications at the construction project level. Based on the above results, the author developed a matrix to map the relationship between technology usage on each work function and productivity in the concrete, structural steel, electrical and piping trades. In addition, a technology index developed from technology usage on all of the work functions were used to investigate the general effect of information technology usage on a project level.

In order to leverage the relative importance of technology on each work function, regression analyses were performed to obtain a further understanding of the relationship. Factor analysis was also applied to identify the latent factors and simplify the patterns of relationships among the different work functions. This analysis could provide construction companies an indication about information technology usage priority and deployment in their work. Finally, a detailed examination of how Building Information Modeling, representing a current significant advancement of information technology usage on many construction projects, impacts the performance of a specific construction project is performed through a case example.

KEYWORDS: Construction, Productivity, Information Technology, Relationship, Automation and Integration

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December 15, 2010

Date

THE RELATIONSHIP BETWEEN INFORMATION TECHNOLOGY AND CONSTRUCTION PRODUCTIVITY

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_________December 15, 2010_________

RULES FOR THE USE OF DISSERTATIONS

Name Date

DISSERTATION

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TO MY PARENTS

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CHAPTER 1 : INTRODUCTION

1.1 Background and Motivation

Information technology (IT) can be defined as the use of electronic machines and programs for the processing, storage, transfer and presentation of information (Björk 1999). As the indicator of the third industrial revolution, information technology has been impacting the economy, the culture and the way of human's life throughout the world. In recent years the IT industry has become one of the largest industries in the U.S., which accounts for 5.38% of the U.S. gross domestic product in 2007 (Bureau of Economic Analysis (BEA) 2009). The IT industry's share in the GDP has even exceeded the construction[1] industry's share in the GDP (4.83% of U.S gross domestic product, Bureau of Economic Analysis 2009). Data from the BEA indicates that during the last two decades the U.S. IT industry experienced a sustained increase in gross output (including sales, or receipts, and other operating income, plus commodity taxes and changes in inventories) (Figure 1.1).

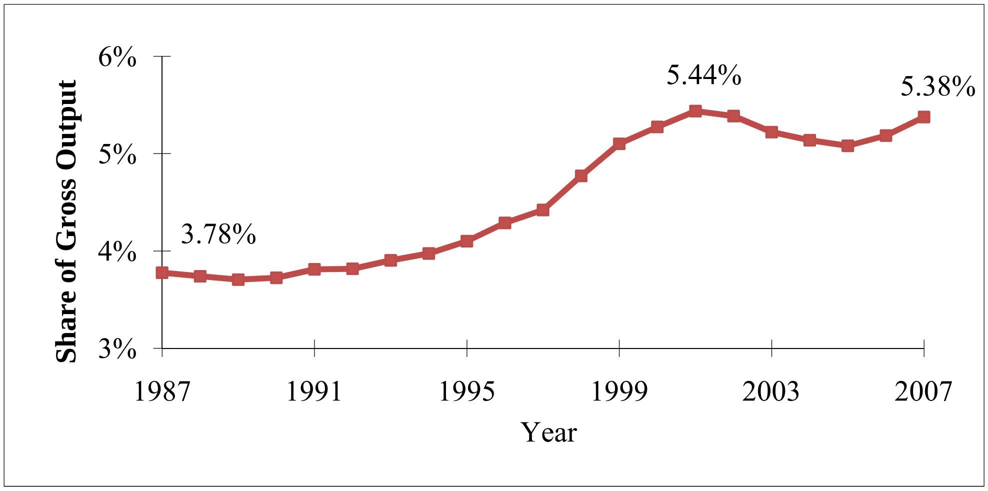

Figure 1.1: U.S. Information Industry's Share in Gross Output, 1987-2007

(Source: US Bureau of Economic Analysis)

Productivity is of central importance to the health of the U.S. economy. With the increasing application of IT in almost all industries, understanding the relationship

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[1] Base on the National Standard Industrial Classification, the construction section includes general construction and specialized construction activities for buildings and civil engineering works. It includes new work, repair, additions and alterations, the erection of prefabricated buildings or structures on the site and also construction of a temporary nature.

between IT and productivity is necessary to improve the effectiveness of IT in improving productivity. Many researchers have investigated the relationship at the following three levels of analysis: 1) national-level, 2) industry-level and 3) firm- or project-level. The focus of these research efforts is to investigate if IT expenditures or related applications in the construction industry contributes to or is associated with productivity improvement. The national-level analysis, comparing the IT usage and productivity across different countries, has the potential to identify if the countries with advanced IT development and application in construction experienced more rapid construction productivity improvement than construction industries in countries with relatively less IT application. The industry-level analysis has the potential to compare the effectiveness of IT application in construction with that of other industries and the resulting impact on the industries' productivity. The firm- or project-level analysis has the potential for providing more detailed information regarding the quantitative relationship between IT application and productivity across multiple construction firms and their projects in the North American construction industry. While previous research has performed these analyses regarding IT application and productivity, none of these research efforts quantitatively examined the general usage of IT on construction productivity, as this dissertation does.

As a result of different research aspects, methods and data sources, different, even contradictory conclusions concerning the trend of construction productivity in the U.S. have been drawn. Previous research efforts using macroeconomic, industrial aggregate data indicated that U.S. construction productivity has underperformed in comparison to both all non-farm U.S. industries and the construction industries of other countries (The Business Roundtable 1982, Bernstein 2003, Tuchman 2004). However, research based on micro measures, e.g. craft activity productivity, indicates that construction productivity has improved (Goodrum et al. 2002, 2004, 2009). Unfortunately, there is still no general consensus concerning the direction of the construction productivity trend in the U.S., since the Bureau of Labor Statistics (BLS) does not maintain a productivity index for the construction industry. One possible reason for the divergence is the problem of aggregate output measurements (Goodrum et al. 2002). In particular, it is believed that the absence of quality measures in the construction industry inflation indices overestimated construction inflation, and thereby underestimated construction real output and construction productivity (Piper, 1990).

Regardless, the construction industry needs to improve productivity (Bernstein 2003). Fortunately, technology has played a crucial role in productivity advancements in both other industries and national economies. In a recent research effort, Triplett and Bosworth (2004) discovered that much of the nation's productivity growth could be attributed to improved production of information technology, increased usage of information technology, increased competition due to globalization, and changes in workplace practices and firm organizations. However, Triplett and Bosworth (2004) also point out that construction bucked this trend by experiencing negative productivity growth between the time periods of their analyses, 1995 to 2001. Many other studies have also shown that the U.S. construction industry has been slow to apply new technologies in comparison to other U.S. industries (Rosefielde and Mills 1979, Business Roundtable 1982). One measure of technology advancement is expenditures on research and development (R&D), and it is clear that construction lags behind other industries in this regard. According to a recent study by Hassell et al. (2001), the construction, building and housing industry invested less than 0.5% of the value of its sales in R&D, while the national average in all industries was approximately 3%. Similar conditions exist in other construction industries elsewhere in the world. For example, in Australia from 1992 to 1997, R&D expenditure in the construction sector averaged only 1.4% of Australia's total R&D expenditure. This was significantly less than the proportion of the Australian construction industry's total output to Australia's total GDP, which averages around 6.5% to 7% (Manseau and Seaden 2001). In other words, the portion of R&D expenditure to value added in the construction sector was less than a quarter of the Australian average. This portion is considered an important indicator of the innovation level of an industry (AEGIS, 1999). Furthermore, within the U.S. construction industry, a lack of information and understanding regarding technological benefits contributes to the reluctance to implement new technologies (O'Connor and Yang, 2004).

There is great hope that IT will eventually have a significant impact on construction projects in North America. One vision predicts that construction sites will become more “intelligent and integrated” as materials, components, tools, equipment, and people become elements of a fully sensed and monitored environment (Wood and Alvarez, 2005). Furthermore, the automation of construction processes could augment manual labor for hazardous and labor-intensive tasks such as welding and high-steel work. In such an environment, the construction environment will be required, whether actively or passively, to process and share larger volumes of data across multiple systems. What remains uncertain in this and other visions of future jobsites is the relative improvement in construction productivity because of the increased automation and integration of construction systems.

In this study, a clear understanding of the relationship between information technology and productivity, especially automation and integration usage in construction, will be obtained by testing whether the projects with advanced technology usage experienced significantly better productivity than those with a relatively low level of technology usage. In addition, the study will leverage the relationship of technology usage on each of the work functions or project tasks to help the construction industry and companies develop strategies for effective implementation of information technology in improving construction productivity.

1.2 Research Objectives

Objectives of this study include:

(1) document IT technology applications in the construction industry that have affected productivity or will have the potential to improve productivity in the future;

(2) investigate the relationship between national IT investment level and construction productivity in various countries;

(3) compare the relationship between IT contribution and productivity in the construction industry with other industries in the U.S.;

(4) identify the relationship of automation and integration usage on work functions/project tasks among typical construction trades in the industrial

construction sector, and thus provide a clear picture of the association between labor productivity and automation/integration usage on information systems at the project level;

(5) identify the latent factors underlying the work functions on which the automation and integration uses have a positive relationship with productivity.

1.3 Research Scope

Productivity is simply defined as the rate of output to input, which is more accurately expressed as Equation 1.1.

$$\text{Total Factor Productivity} = \frac{\text{Total Output}}{\text{Labor} + \text{Materials} + \text{Equipment} + \text{Engergy} + \text{Capital}} \qquad (1.1)$$

Total factor productivity (TFP) is a widely used economic model measured in capital unit, such as dollars. TFP is synonymous with multi-factor productivity (MFP). TFP is useful for policy-making, evaluating the state of the economy and making comparisons between countries, but it is hard to measure (Thomas et al. 1990). At the project level, a contractor is more likely to use labor productivity (Equation 1.2), which relates output to the quantity of man-hours, such as tons of structural steel installed per hour (The Business Roundtable 1982).

$$\text{Labor Productivity} = \frac{\text{Total Output}}{\text{Quantities of Man-hours}} \qquad (1.2)$$

However, compared to TFP, labor productivity may not really reflect the long-run productivity because it does not capture the impact of other inputs. For example, using advanced material tracking technologies may drastically improve a project's labor productivity, but productivity measured by TFP may not be improved due to extra capital expenditures in construction tools or equipment.

In this research, the analysis will include only labor productivity, for several reasons. First, there is no reliable data source to provide industrial MTP in construction. Second, a major dataset used in this research is project-specific, and collected in a relatively short term. However, IT investments have been found to require about five years before a break-even point is reached (Brynjolfsson, 1993), so it is difficult to observe the change of factor productivity as a possible result of implementing an information technology in the short term. Third, the construction industry is labor intensive; labor is the prime economic resource, and on-site labor costs typically contribute 30% to the overall project's costs (McNally et al. 1967, McTague and Jergeas 2002). Similarly, the Business Roundtable (1982) reported that labor constitutes 25% of direct capital cost of a project. Therefore, an improvement in labor productivity indicates an improvement of capital effectiveness in a project. That said, the author acknowledges that technology in general has a greater influence on labor productivity than factor productivity, which relates to the labor savings bias of technical change (Salter 1966).

Finally this study will limit its project level investigation to the industrial construction sector, since all projects contributing to this research are selected from Construction Industry Institute (CII) member companies, and most of their projects are involved in this area. Labor productivity data will include only the concrete, structural steel, electrical and piping trades, which are the most common trades on industrial projects. The technologies will also be limited to the automation and integration of information technology systems in construction.

CHAPTER 2 : BACKGROUND AND LITERATURE REVIEW

This chapter summarizes the previous research on the construction productivity trends, and then discusses technology (especially IT) application on construction and other industries. It concludes by outlining the relationship between technology usage and productivity.

2.1 Research on the Trend of Construction Productivity

Studies completed in the 1980s reported that construction real output (value added) per work hour declined by an annual rate of 2.4% to 2.8% between 1968 and 1980 (Stokes 1981, BRT 1983, Allen 1985). More recently, studies using industry data from the U.S. Department of Commerce and the U.S. Bureau of Labor Statistics indicate that construction's labor productivity declined from 1964 to 2000 at an annual compound rate of 0.72% (Teicholz 2000).

Other evidence contradicts these figures. Previous research examined labor and partial factor productivity trends using microeconomic data for 200 activities (Goodrum et al. 2002a). The results indicated widespread improvement in construction productivity across multiple construction divisions, ranging from 0.2% to 2.8% per year between 1976 and 1998, especially in machinery dominated divisions such as site work. Similarly, using the output and work hour data for the period under study (1977-2004), another research effort investigated the change of labor productivity between 1977 and 2004 for 100 sampled activities (Goodrum et al. 2009). The result indicated that the average percentage of change in the labor productivity between 1977 and 2004 was 13.5%, with an annual improvement compound rate of 0.47%. In addition to these measured improvements, there is also much anecdotal evidence shared by industry leaders that productivity has actually improved (Bernstein 2003, Tuchman 2004, Harrison 2007).

The potential reasons to explain the discrepancy between macro and micro measures of construction productivity are numerous with most of the focus on issues regarding the accuracy of industry measures, particularly on the inflation indices used to measure industry real output. The concerns range from over reliance on the use of proxy inflation indices to deflate construction expenditures (Pieper 1990), the use of input cost inflation indices instead of the preferred output price indices (Dacy 1965, Gordon 1968, and

Pieper 1990), and the challenge of measuring the change in the quality of industry output (Rosefielde and Mills 1979, Pieper 1990, Gullickson and Harper 2002). The cumulative effect of these concerns is that a productivity index does not exist for the U.S construction industry. Another result of these concerns is that the U.S. Census Bureau no longer maintains a constant dollar series of the Value of Construction Put in Place Statistics, which are the primary source of industry output measures. However, examining construction at a micro level (i.e. at the trade and activity level) helps avoid many of the inaccuracies.

2.2 Research on Technology usage (Mainly IT Usage on Construction)

Although the construction industry has been considered technically stagnant, there have been an increasing number of new technologies, especially information technologies, applied within it. Many previous research efforts have investigated and documented the application of new technologies in construction.

Ahmad et al. (1995) studied the technology needs and IT applications in construction (Table 2.1), which indicated how IT's characteristics satisfy the needs of construction. This research was intended to help the construction industry adopt various information technologies more purposively and assist in selecting proper IT tools for various tasks.

Table 2.1: Technology Needs and IT Applications in Construction

Need (1)	IT capbilities (2)	IT tools (3)
Integration Coordination Training Supervision	Communication	Voice mail/Email/Fax Electronic network Document imaging Mutimedia
Internal(project/company)and external standards Data capturing, storage, retrieving and transmitting	Data accessibility	Share databases Electronic data interchange(EDI) Bar code 3-D graphics
Decision making Consensus reaching Technical analysis	Common systems	Knowledge-base systems Decision systems Groupware Executive information systems

Source: Ahmad et al. (1995)

O'Connor and Yang (2004) conducted research to determine the extent, if any, to which integration and automation (IA) technologies contributed to project success. The researchers divided the project life cycle into six phases: front end, design, procurement, construction management, construction execution and startup/operations/maintenances. Each phase was composed of work functions, some of which represented project tasks (for possible automation), and some of which represented task-to-task integration links. The researchers identified 68 work functions in six phases that make up a project's life cycle as follows.

Phase 1: Front end Planning

1.01: Conduct market analysis or need analysis for a new facility
1.02: Develop, evaluation, and refine the project's scope of work
1.03: Diagram the manufacturing process
1.04: Estimate a budget from the scope of work
1.05: Prepare milestone schedule
1.06: Acquire and store site investigation data for use during design

Phase 2: Design

2.01: Access supplier product information
2.02: Input on construction methods and sequencing
2.03: Analyze construction methods
2.04: Detailed design from conceptual design
2.05: Prepare floor plans
2.06: Design fluid systems
2.07: Design structural systems
2.08: Design electrical systems
2.09: Design HVAC systems
2.10: Document the assumptions used in developing the budget, and pass to the next phase
2.11: Detect physical interference
2.12: Prepare specifications
2.13: Check the design against owner requirements and code requirement
2.14: Track design progress

Phase 3: Procurement

3.01: Determine procurement lead time
3.02: Conduct a quantity survey of drawings
3.03: Link quantity survey data to the cost estimating process
3.04: Link supplier quotes to cost estimate
3.05: Refine the preliminary budget estimate
3.06: Develop the milestone schedule
3.07: Transmit requests for proposal to suppliers and subs
3.08: Prepare & submit shop drawings
3.09: Acquire & review shop drawings
3.10: Compile quotes into bid
3.11: Monitor fabricator progress
3.12: Plan transport routes

Phase 4: Construction Management

4.01: Develop the construction schedule

4.02: Tract field work progress & labor cost code charges
4.03: Maintain daily job diary
4.04: Update cost forecast
4.05: Communication construction progress
4.06: Track site material inventory
4.07: Link field material managers to suppliers
4.08: Develop short-term work schedules
4.09: Communicate requests for Information & responses
4.10: Provide feedback about the effects of design changes
4.11: Communicate changes to field
4.12: Communicate status of change orders to field
4.13: Update as-built drawings
4.14: Submit request for payment
4.15: Transfer funds from owner's account to contractor

Phase 5: Construction execution

5.01: Evaluate subsurface conditions
5.02: Carry out earthwork and grading
5.03: Fabricate rebar cages
5.04: Weld pipes
5.05: Select the appropriate crane for heavy lifts
5.06: Provide elevated work platform
5.07: Fabricate roof trusses
5.08: Manipulate/hang sheet rock
5.09: Acquire & record laboratory test information
5.11: Apply paint/coatings

Phase 6: Startup, operations, & maintenance

6.01: Conduct pre-operations testing
6.02: Train facility operators
6.03: Use as-built information in personnel training
6.04: Track equipment maintenance history
6.05: Develop equipment maintenance plans

6.06: Monitor & assess equipment operations
6.07: Facility operators request maintenance or modifications
6.08: Update as-built drawing
6.09: Monitor facility energy consumption
6.10: Monitor environmental impact of facility operations

The researchers developed an IA (integration and automation) index ranging from 0 to 10 according to its use level on each of work functions. Through statistical analyses, this research indicated that:

- The schedule success-technology relationship was stronger than that for cost;
- Higher levels of project schedule success were particularly associated with high levels of technology utilization for building, medium-sized, and expansion projects;
- Higher levels of project schedule success were associated with high levels of technology usage in the front-end phase, particularly for building and medium-sized projects.

Other researchers found similar results regarding IT usage and firm performance (El-Mashaleh et al. 2006). The researchers examined the impact of information technology on construction firm performance. Data for the research was collected through a Web-based survey. Respondents were asked to provide information regarding firm performance metrics (Table 2.2) and to rate the level of IT utilization for each of work functions.

Table 2.2: Metric of Performance that Composes Firm Performance

Metric	Method of measurement
Schedule performance	Percent of the time projects are delivered on/ahead of schedule
Cost performance	Percent of the time projects are delivered on/under budget
Customer satisfaction	Percent of repeat business customers
Safety performance	Experience modification rating
Profit	Net profit after tax as a percent of total sales

Source: El-Mashaleh et al. (2006)

Analyses provided empirical evidence that IT was positively associated with firm, schedule, and cost performance. Through a similar method to O'Connor and Yang's (2004), the researchers developed an IT index ranging from 0 to 10 according to its use level on each project work functions. The regression analysis showed that for every 1 unit increase in IT utilization, based on the index's scoring, there was an increase of about 2%, 5%, and 3% in firm performance, schedule performance, and cost performance respectively. The method used to develop the integration and automation index in the above two researches, can help assess the IT application level in this dissertation research.

Rivard (2000) investigated the impact of IT on the Canadian architecture, engineering, and construction industry. He found that many business processes were almost completely computerized and the tendency was toward a greater computerization of the remaining processes, according to a survey on the impact of information technology on the Canadian architecture, engineering, and construction industry. Although the Internet had been adopted by most firms surveyed in his research, design information was still exchanged in its traditional form, i.e. paper-based rather than electronic form, which the author felt was an indication that the construction industry was unwilling to use available advanced technology. These firms had increased and would increase further their investment in IT, which had raised productivity in most business processes and had resulted in an increase in the quality of documents and in the speed of work, better financial controls and communications, and simpler access to common data. However, this research did not indicate the magnitude the impact of information technology.

Automation is one of the typical characteristics of information technology. Navon (2005) described fully automated project performance control of various project performance indicators. The measurement of labor productivity can be automated, using an indirect approach—the location of the workers is measured at regular time intervals and converted into productivity. In addition, the performance control of materials management and worker's safety can also be automated. The automated performance control can help managers obtain instant construction information (e.g. productivity) more quickly, examine the execution of construction plan and make next-step decision.

Obviously, the effectiveness of construction management can lead to the improvement of a project's productivity.

Thomas et al. (2004) evaluated impacts of Design/Information Technology (D/IT) on project outcomes. In this research D/IT specifically included the use of four technologies: integrated database, electronic data interchange (EDI), three-dimensional (3D) computer-aided design (CAD) modeling, and bar coding. The researchers indicated that the use of D/IT and project performance was positively correlated. The researchers also developed an index using a method similar as O'Connor and Yang's (2004) to assess the D/IT use level. The researchers found that both owners and contractors can expect approximately 4% cost savings in their projects by increasing the use of D/IT from a low to a high level. For owners, there was clear evidence of schedule compression as well. Although the statistical analyses did not support schedule compression benefits for contractors, findings from the on-site interviews provided anecdotal support. Project size was the single most important factor for determining the degree of use for these technologies on most projects. Fortunately, as the cost of implementing these technologies continue to fall, it is likely that there will be increased use on smaller projects. It can be expected that this research will prompt the D/IT application in construction.

A research by Balli (2002) proved that handheld computers in conjunction with wireless networking technologies could provide accurate, reliable and timely information to construction project players at the location that it is needed. The handheld computers would allow people to access material, tool, equipment and drawing information, which could reduce delay time and boost productivity.

Global Positioning Systems (GPS) and Radio Frequency Identification Technology (RFID) are two important intelligent tracking and locating technologies used in construction. Caldas et al. (2006) indicated that the application of GPS not only provided direct time savings in the material-locating process, but it also reduced the number of lost items, work disruption and labor idle-time. In addition, it could improve standardization and automation of locating process, route optimization, layout optimization, and data entry. Ergen (2006) stated that an automated material tracking system using radio frequency identification technology combined with GPS technology could eliminate the deficiencies in existing manual methods of identifying, tracking and locating highly customized prefabricated components. The application of using RFID on construction was also discussed by Furlani and Stone (1999) and Furlani and Pfeffer (2000). These researches presented a promising future of GPS and RFID, as the typical IT application in the construction industry.

Intelligent tracking is also an important application of IT in manufacturing (Brewer et al., 1999). The various forms of intelligent tracking technologies (IT2) included global positioning systems (GPS), geographic information systems (GIS), wireless telecommunications, and radio frequency identification (RFID). The technology has the potential to contribute to improvements to manufacturing. This research provided a list of benefits of the wireless RFID system and discussed how scheduling of event times could become more accurate and time wasted could be minimized. It also showed that the RFID coupled with GPS could greatly change production quotas and connect customers and suppliers more efficiently.

Range-free techniques are those techniques which do not use signal strength for distance measurement. One research by He et al. (2003) described a range-free localization scheme (APIT). The authors compared the performance of their algorithm with the performance of the other well-known range-free techniques. The comparison showed that this technique provided better accuracy. It seemed that the APIT technique was a simple approximate technique and since sensor networks did not need very accurate location estimates, this technique which was quite similar to the accumulation array method (a proximity localization model introduced by Song et al. 2007) might be good enough for many sensor applications.

The use of Building Information Modeling (BIM) has recently expanded. According to a survey of thousands AEC participants in North America conducted by McGraw_Hill Construction in 2009, almost 50% of the industry was using BIM. There are different definitions of BIM, and McGraw_Hill Construction defines BIM as the process of creating and using digital models for design, construction and/or operations of projects. BIM is not only a kind of software or a tool, but a concept of visualization, integration and interoperability. Heller and Bebee (2007) summarized the benefits of BIM as follows:

- BIM fosters greater collaboration between project stakeholders, inspires ingenuity on site and leads to more productivity.
- BIM helps companies streamline business processes in terms schedule optimization, and automated cost estimating.
- BIM is able to pick up coordination issues early on that would have been costly.
- BIM minimizes the errors in the field.
- BIM contributes to companies' savings and productivity increase.
- BIM's visualization features increases quality and efficiency.

In a case study, Lamb (2009) reported significant cost and time savings as a result of using BIMs application on two projects. Moreover, the productivity for installing the mechanical and electrical systems on these same projects was reported to 5% and 30% above the construction industry standards.

2.3 Research on the General Industrial Relationship between Information Technology and Productivity

During the 1980s, the relationship between information technology and productivity at a general industry level became a source of debate. Previous research cited the lack of empirical evidence to support the positive economic impact of information technology the "IT productivity paradox" (Solow 1987, Roach 1991, Brynjolfsson 1993).

Brynjolfsson (1993) indicated that on one hand, delivered computing-power in the U.S. economy had increased by more than two orders of magnitude in the past two decades (Figure 2.1); on the other, productivity, especially in the service sector, seemed to have stagnated (Figure 2.2). Although Snow (1966) considered IT effects as "the biggest technological revolution men have known", different or even contrary opinions existed such as "Computer Data Overload Limits Productivity Gains" (Zachary, 1991). A widely cited study by Loveman (1994) even showed that the marginal contribution of IT to productivity was negative. The contradiction between the expectation of IT's effect on productivity and the real statistical result has been termed by many prior researchers as, "the productivity paradox."

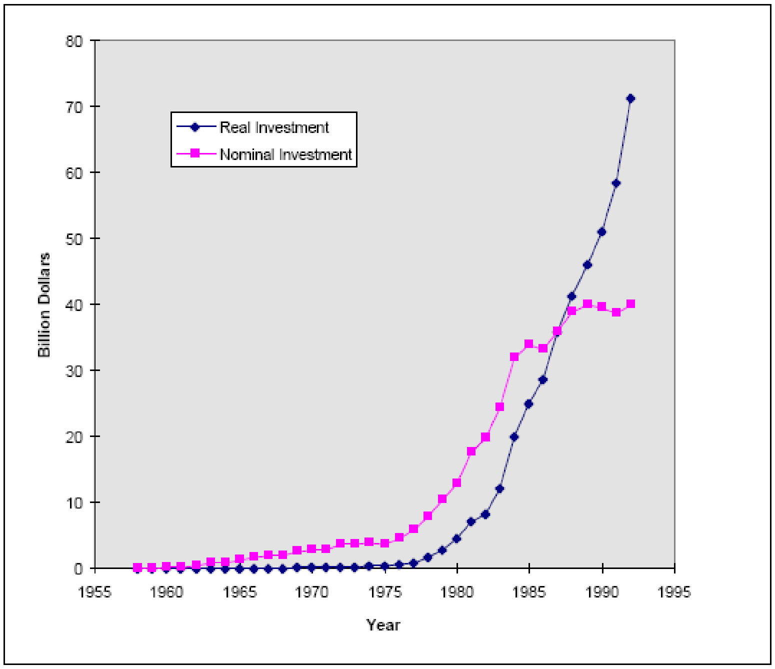

Figure 2.1: Investment in Information Technology Growing at a Rapid Pace

Source: Based on data from BEA, National Income and Wealth Division, adapted from Jorgenson and Stiroh (1995).

Note: Constant dollars (base year 1987) calculated by hedonic price method, see Dulberger (1999).

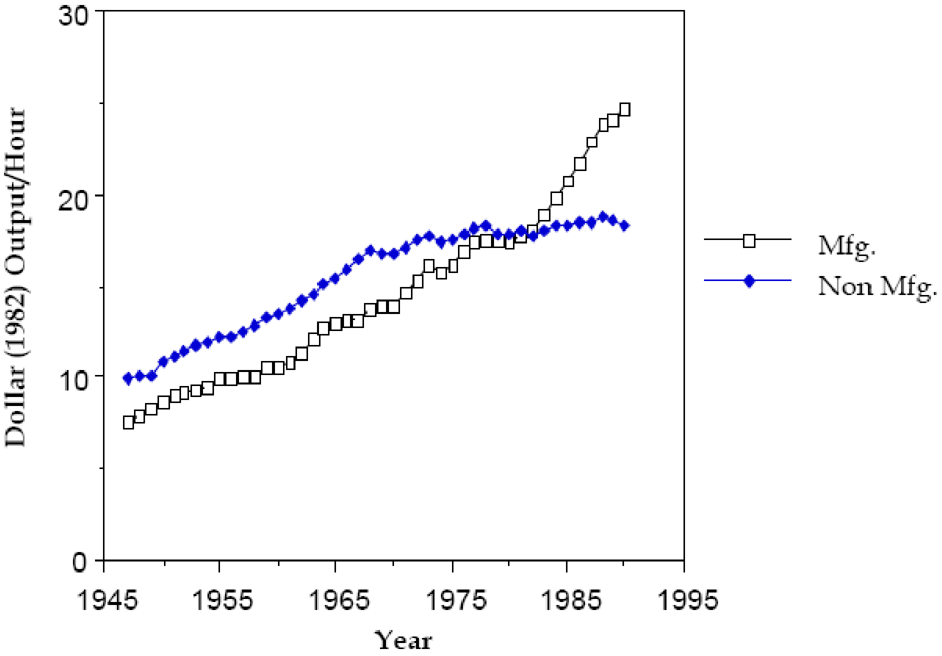

Figure 2.2: Stagnant Productivity in the Service Sector

Source: Based on data from Bureau of Labor Statistics, Productivity & Testing

The explanations of the productivity paradox can be grouped into four categories (Brynjolfsson, 1993):

1) Inaccurate measurement of outputs and inputs. The easiest explanation for the confusion about the productivity of information technology was simply that researchers were not properly measuring output. The sorts of benefits that managers ascribed to information technology—increased quality, variety, customer service, speed and responsiveness—were precisely the aspects of output measurement that were poorly accounted for in productivity statistics as well as in most firms' accounting numbers (Brynjolfsson, 1994).

2) Lags due to learning and adjustment. The benefits from information technology could take several years to appear on the bottom line. The idea that new technologies may have a delayed impact is a common one in business.

3) Redistribution and dissipation of profits. Information technology may be beneficial to individual firms, but unproductive from the standpoint of the industry or the economy as a whole: IT rearranged the shares of the total profit without increasing it.

4) Mismanagement of information and technology. It was possible that overall IT really was not productive at the firm level. The investments were made nevertheless because the decision-makers were not acting in the interests of the firm. Instead, they were increasing their slack, signaling their prowess or simply using outdated criteria for decision-making.

Recent research has been more encouraging, as new data was identified and more sophisticated methodologies of analyses were applied.

Dewan and Kraemer (2000) studied the relationship between IT and productivity at the national-level. They found significant differences between developed and developing countries with respect to their structure of returns from capital investments. For the developed countries in their sample, returns from IT capital investments were estimated to be positive and significant, while returns from non-IT capital investments were not commensurate with relative factor shares. The situation was reversed for the developing countries subsample, where returns from non-IT capital were quite substantial, but those from IT capital investments were not statistically significant. The countries' IT investment and Relative 1990 GDP per Worker are shown in Figure 2.3.

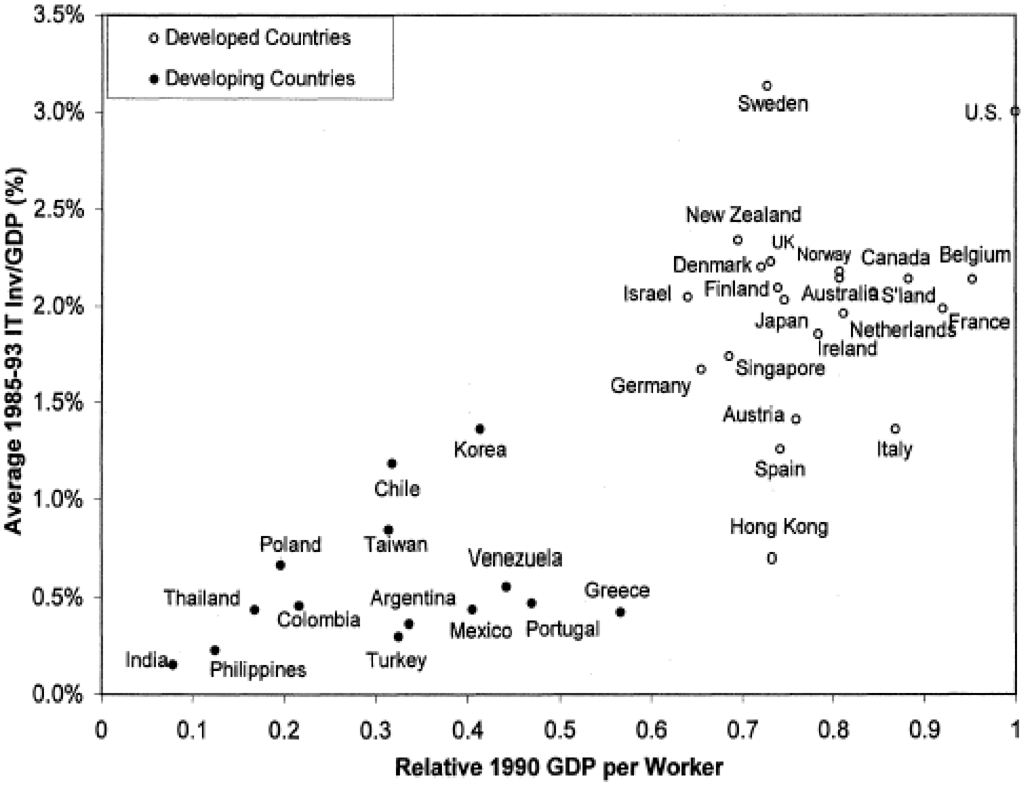

Figure 2.3: Scatter Plot Between Average 1985-1993 Annual IT Investments as a Percentage of GDP against Relative (to U.S.) 1990 GDP per Worker

Note: Both Variables Measured in Terms of Constant 1990 International Dollars
Soucre: Dewan and Kraemer (2000)

There have also been many firm-level studies that observed a positive relationship between IT application and productivity in various industries, such as service, manufacturing and banking. Brynjolfsson and Hitt (1993) found that for the service firms sampled in their research, return on investment of information technology averaged over 60% per year. In another research, Brynjolfsson and Hitt (1996) found that IS (information system) spending had made a substantial and statistically significant contribution to firm output and the gross marginal product for computer capital averaged 81% for the sampled firms.

Diewert and Smith (1994) provided an interesting case study of a large Canadian retail firm. They derived a consistent accounting framework for the treatment of inventories when measuring the productivity of a distribution firm. According to their research, the firm achieved a 9.6 percent per quarter total factor productivity growth rate over 6 quarters. They concluded that these productivity gains were made possible by the computer revolution, which allowed a firm to track accurately its purchases and sales of inventory items and to use the latest computer software to minimize inventory-holding costs.

Alpar and Kim's (1991) study of 759 banks demonstrated the cost-reducing effects of IT. A 10% increase in IT capital was associated with 1.9% decreases in total costs. Harris and Katz (1991) analyzed the insurance industry data and found a positive relationship between IT expense ratios and various performance ratios. The longitudinal analysis showed that the firms with the most improvement in their organizational performance exhibited greater premium income growth, lower operating costs growth, lower non-information technology costs growth, higher growth in the IT expense ratio, and larger reductions in the ratio of IT costs to premium income.

Siegel (1994) investigated the relationship between IT and manufacturing productivity. He observed that computers may exacerbate errors in the measurement of productivity: firms invest in computers not only for cost reduction but also for quality improvement. He found a positive and statistically significant relationship between productivity growth and investments in computers. But he did not think this truly established causality. Still, this result suggested that the productivity paradox, or the absence of a positive correlation between computers and productivity growth, at least in the manufacturing sector, could be a statistical illusion due to measurement error.

Although Siegel's study focuses on the manufacturing sector, the findings may have even stronger implications for services. Baily and Gordon (1988) reported that service industries invest in computers at approximately double the rate of manufacturing industries. There was also a strong consensus among economists (Griliches, 1992) that errors of measurement of productivity growth were more severe in the service sector. Baily and Gordon (1988) concluded that many of these errors had probably resulted in an understatement of productivity growth. Much of this mismeasurement has been attributed to difficulties in quality adjustment.

As shown above, there are many evidences that IT application positively correlated to productivity in other industries, but the relationship in the construction industry is still unknown, which motivates this research.

2.4 Research on the Relationship between Technology Use and Construction Productivity

Construction productivity has attracted much attention and discussion in the past decades. Many researchers have investigated the factors that can impact construction productivity. Innovation and the adoption of new technologies in the construction industry was perceived as the only effective solution that would enhance the quality of the building product, increase construction efficiency, and decrease costs (Ioannou and Carr, 1988). Allmon et al. (2000) indicated that technology application can greatly impact construction productivity. But the introduction of new technologies in the construction industry has traditionally lagged behind other industries (Rosefielde and Mills 1979, Business Roundtable 1982, Dulaimi 1995). For example, the construction industry has not adopted robotics to the extent that other industries have. It was widely accepted that automation and robots were the magical solution to industry wide problem of increasing costs, declining productivity, skilled labor shortages, safety and quality control (Everett, 1994). However, despite the millions of dollars spent on the research and development of new technologies, few of those innovations were being used by the construction industry (Everett, 1994).

Regardless, there are still significant technical advances in construction techniques, machinery, and methods. For example, advancements in on-board microprocessors and hydraulic controls allow excavator operators to more precisely control their boom and shovel position, to function with larger operating envelopes, to more accurately monitor engine and other system parameters, and to quickly diagnose critical system failures.

Three important research studies investigated the relationship between construction productivity and technology usage. Goodrum and Haas (2004) studied the long-term impact of equipment technology on labor productivity in the U.S. construction industry at the activity level. First, the research examined 200 construction activities for the effect of technology, specifically equipment technology, on their labor productivity from 1976 to 1998. The average improvement in labor productivity for the sampled activities over the 22-year period was 30.93% with an annual improvement compound rate of 1.23%. Second, the researchers examined equipment technology changes over the 22-year period using five equipment technology characteristics: level of control, amplification of human energy, information processing, functional range, and ergonomics. The technology index was calculated with Equation 2.1:

$$\text{Equipment Technology index}=\frac{\sum_{1}^{N}(\Delta E+\Delta C+\Delta F+\Delta R+\Delta I)}{N}, \qquad (2.1)$$

where ΔE =change in energy; ΔC =change in control; ΔF =change in functional range; ΔR =change in ergonomics; ΔI =change in information processing; and N=number of tools and machinery in the activity.

Third, the relationship between equipment technology changes and labor productivity changes in construction was examined. First, using the technology factors, analysis of variance (ANOVA) indicated that with the exception of ergonomics, the activities that experienced improvement in equipment technology experienced more improvements in labor productivity that those activities that did not, and this finding was statistically significant (Figure 2.4). Next, a series of simple and multiple regressions were used to further examine the relationship between equipment technology and labor productivity.

The researchers reached the following conclusions:

1) Most of the study's 200 activities experienced improvements in labor productivity from 1976 to 1998, confirming other research using activity level data and contradicting research using aggregated level data.

2) Technological advances explained some of the labor productivity increase from 1976 to 1998.

3) Substituting equipment technology for labor provides additional explanation of the increase.

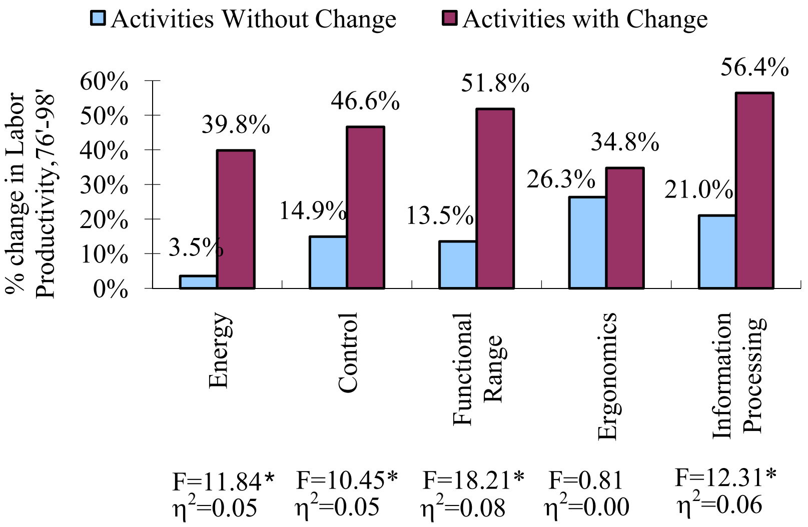

Figure 2.4: Percent Change in Labor Productivity for Activities with a Change in Equipment Technology and Activities with no Change in Equipment Technology, 1976-1998, $^*p<0.05$

An earlier research conducted by Goodrum and Haas (2002) found the similar result in respect of the relationship of change in partial factor productivity and equipment technology. Through ANOVA and regression analyses, it was found that activities that experienced a significant change in equipment technology also witnessed substantially greater long-term improvements in partial factor productivity than those that did not experience a change (Figure 2.5).

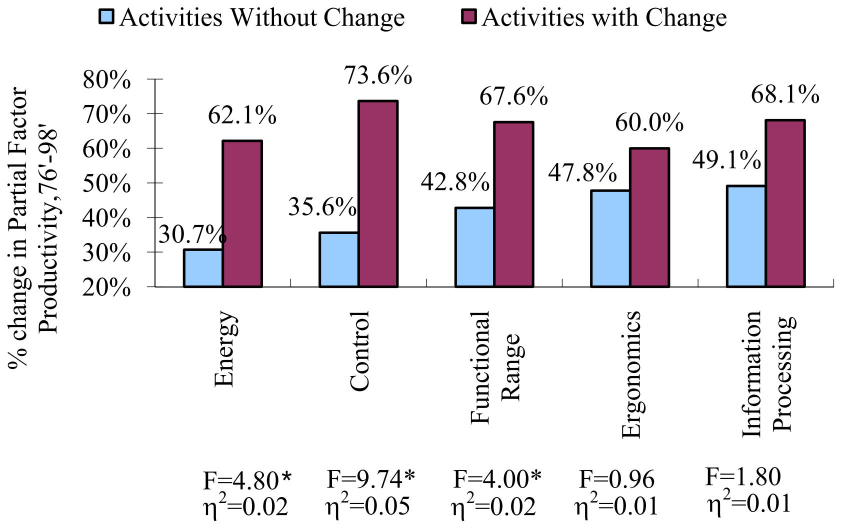

Figure 2.5: Percent Change in Partial Factor Productivity for Activities with a Change in Equipment Technology and Activities with no Change in Equipment Technology, 1976-1998, *p<0.05

Besides equipment technology, material technology has also proved to positively relate to construction productivity (Goodrum et al. 2007). By analyzing the changes in both material technology and productivity among 100 construction activities from 1977 to 2004, this research examined the strength and types of relationships that exist within these two changes. Through analysis of variance (ANOVA) and regression analyses, the researchers found that activities experiencing significant changes in material technology had also experienced substantially greater long-term improvements in both their labor and partial factor productivity (Figure 2.6 and 2.7). The research did find that a stronger relationship existed between changes in material technology and partial factor productivity than in labor productivity. The research also found that changes in the unit weight of materials had a significant relationship to labor productivity, while changes in installation and modularity had a significant relationship to partial factor productivity.

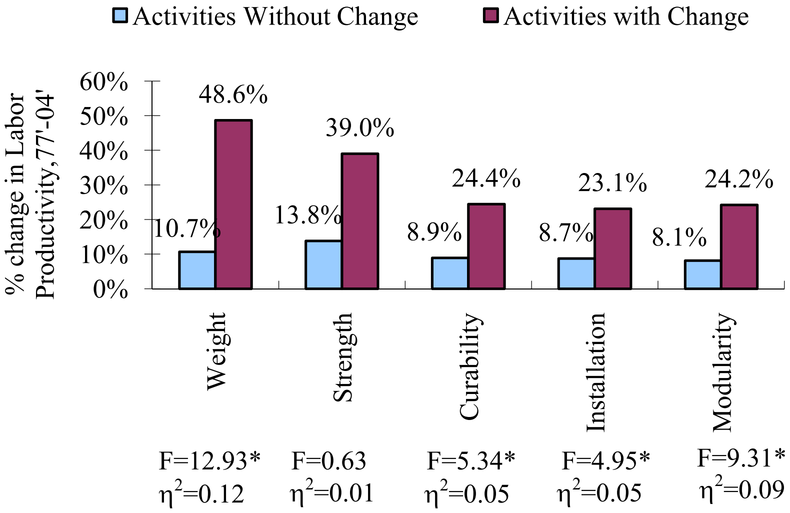

Figure 2.6: Percent Change in Labor Productivity for Activities with a Change in Material Technology and Activities with no Change in Material Technology, 1977-2004, $*p<0.05$

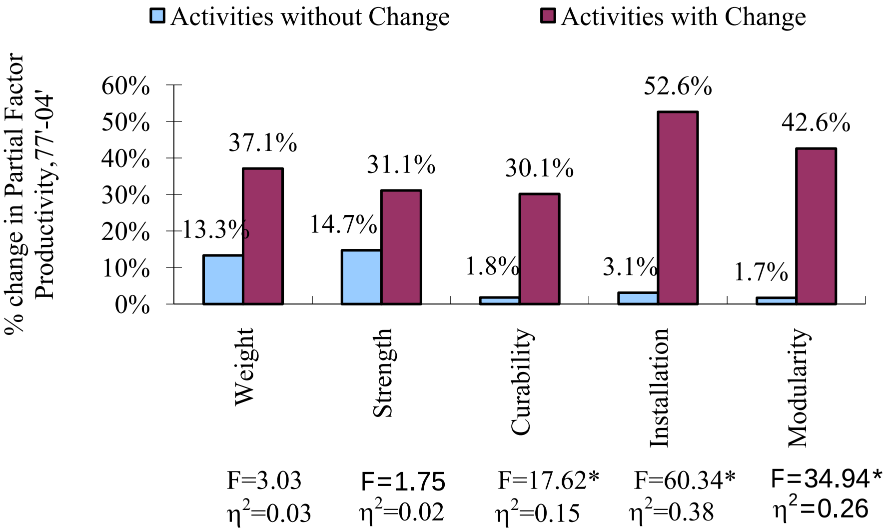

Figure 2.7: Percent Change in Partial Factor Productivity for Activities with a Change in Material Technology and Activities with no Change in Material Technology, 1977-2004, $*p<0.05$

Eastman and Sacks (2008) compared the relative productivity of construction industry with significant off-site fabrication with more traditional on-site sectors. Used the data from the Census of Manufacturing and the Census of Construction, the labor productivity in this article was defined as value added per employee. The economic data is presented and comparisons between off-site and on-site activity were drawn in two ways: (1) within sectors that have both significant on-site and off-site labor components (curtainwalls, structural steel, and precast concrete; and (2) between wholly on-site sectors (drywall and insulation, cast-in-place concrete) and sectors that are predominantly off site (elevators and moving stairways). The off-site production of building components was observed significantly more labor productive in contrast to related on-site activities. Not only did they have a higher level of labor productivity, but their rate of overall productivity growth was greater than comparable on-site sectors. Typically, the off-site productivity grew by 2.32% annually, while the on-site productivity grew by 1.43% (Figure 2.8). This research also identified one of the important reasons why construction productivity was significantly underestimated from the aggregate level: the off-site sectors, which were more productive, were not traditionally considered as part of construction industry by the U.S. Economic Census, but rather as manufacturing.

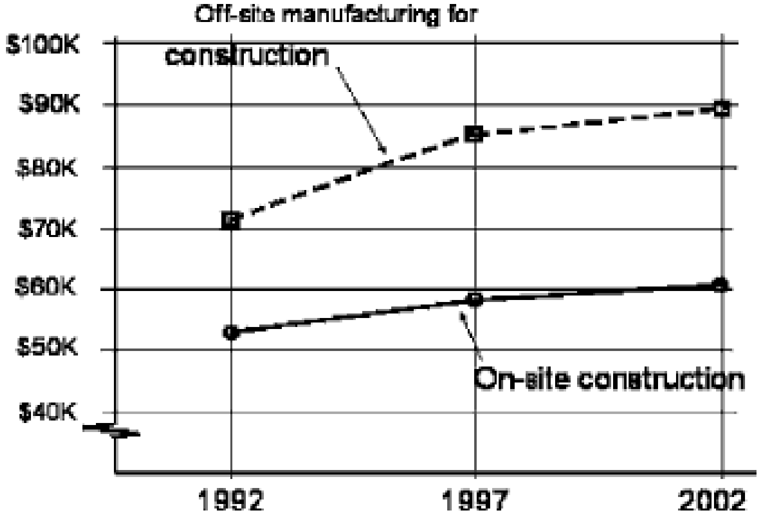

Figure 2.8: Aggregate value added for off-site construction manufacturing for construction and comparable on-site industry sectors

Source: Eastman and Sacks (2008)

2.5 Summary

Through literature review, the author identified the following conclusions:

(1) There were contradicting opinions in regard to the trend of construction productivity: the aggregate level data indicated a decreasing trend, while the micro- or activity-level data indicated an increasing trend. The difficulty of real output measurement may account for the inconsistency.

(2) There were many researches that investigated the impact of IT application on construction. Many of these technologies improved the project or firm performance, but none of these research provided specific information about how IT impacted construction productivity.

(3) Many researchers have observed positive association between IT application and productivity in the industries other than construction.

(4) Construction equipment and material technology are positively correlated to construction productivity at the activity level.

Therefore, it is clear that what remains unknown is whether there is a positive relationship between IT application and construction productivity. If yes, what is the magnitude of the effects? This is the major question that will be investigated in this research.

CHAPTER 3 : METHODOLOGY

This research investigated the relationship between information technology and productivity. The main hypotheses of this study are: (1) the investment of information technology has a positive relationship to construction productivity; (2) the contribution of IT capital to an industry's value added growth has a positive relationship to this industry's labor productivity improvement; and (3) the projects with a high level automation/integration usage of information systems have significantly greater productivity than those with a low level. The author tested the three hypotheses through three levels' analyses.

3.1 National-level Analysis

The purpose of this analysis is to investigate the relationship of IT development and application to construction productivity in various countries. In addition, it helps to identify the standing of the U.S. regarding the effectiveness of IT application compared with other countries. The data used in this section are from Organisation for Economic Co-operation and Development (OECD) and The Groningen Growth and Development Centre (GGDC). OECD is one of the world's largest and most reliable sources of comparable statistics and economic and social data. As well as collecting data, OECD monitors trends, analyses and forecasts economic developments and researches social changes or evolving patterns in

trade, environment, agriculture, technology, taxation and more. Currently, 30 countries have joined in the OECD including the U.S., Canada, Mexico, Australia, New Zealand, Japan, Korea and the European Community. GGDC was founded in 1992 within the Economics Department of the University of Groningen by a group of researchers working on comparative analysis of levels of economic performance and differences in growth rates. The center compiles and maintains a range of comprehensive databases on indicators of growth and development on a regular basis. Due to the availability of data in both databases, 17 countries were included in analysis as follows: Australia, Austria, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, Portugal, Spain, Sweden, United Kingdom and United States.

3.1.1 IT Development Measurement

To benchmark the development, application and impact of information and communication technology[2], the European Union (EU) launched a program in 2005, named the i2010, which identified a list of key indicators to measure IT usage within specific EU countries. The indicators are grouped under nine themes: (1) Developments in broadband, (2) Advanced services, (3) Security, (4) Impact in relation to the overall Lisbon objectives of growth and employment, (5) Investment in Information and Communication Technology (ICT) research, (6) Adoption of ICT by businesses, (7) Impact of adoption of ICT by Business, (8) Inclusion and (9) Public services. Unfortunately, the i2010 research is relatively new, and cannot be used in the historical analysis conducted in this paper.

OECD also identified 15 ICT indicators from various publications and databases produced by the OECD's Directorate for Science Technology and Industry (DSTI):

1. Access lines and access paths in total / per 100 inhabitants for OECD
2. Mobile subscribers in total / per 100 inhabitants for OECD
3. Internet subscribers in total for OECD

4a. Broadband subscribers per 100 inhabitants in OECD countries
4b. Availability of Digital Subscriber Lines (DSL) in OECD countries
5. Cable TV subscribers in total for OECD
6a. Households with access to a home computer
6b. Households with access to the Internet in selected OECD countries
6c. Households with access to broadband in selected OECD countries
7a. Internet penetration by size class
7b. Internet selling and purchasing by industry
8a. Share of ICT-related occupations in the total economy in selected countries, narrow definition

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[2] Information and communication technology, usually called ICT, is often used as a synonym for information technology (IT) but is usually a more general term that stresses the role of telecommunications (telephone lines and wireless signals) in modern information technology. ICT consists of all technical means used to handle information and aid communication, including both computer and network hardware as well as necessary software. In other words, ICT consists of IT as well as telephony, broadcast media, and all types of audio and video processing and transmission.

8b. Share of ICT-related occupations in the total economy in selected countries, broad definition

9a. Telecommunication services revenue in total for OECD

9b. Mobile telecommunication services revenue in total for OECD

9c. Telecommunication infrastructure investment in total for OECD

10a. Share of ICT value added in the business sector value added

10b. R&D expenditure in selected ICT industries

10c. Share of ICT employment in business sector employment

11a. ICT-related patents as a percentage of national total (PCT filings)

11b. Share of countries in ICT-related patents filed under the PCT

12. Trade in ICT goods

13. Top 50 telecommunications firms and IT firms

14. Contribution of ICT-using services to value added per person engaged

15. Contributions of ICT investment to GDP growth

Similar to the indicators of the i2010, these 15 indicators are also available only in very limited years and countries and thus cannot be used in this research.

Therefore, the author used the ICT investment as the percentage of non-residential gross fixed capital formation[3] as the indicator of IT development in one country as previous researchers have done (Dewan and Kraemer, 2000). The authors acknowledge that the ICT investment described herein is not limited to just construction but across all industries among the sampled countries. The expenditure or investment of information technology in the construction industry is obviously a better indicator of IT application level in construction, but this level of detailed data is rarely available. It is true that the average level of information technology in one country may be not able to represent the IT application level in its construction industry, but to some extent, this hypothesis can be used in the comparison between different countries, because generally speaking, the

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[3] Gross fixed capital formation (GFCF) is a macroeconomic concept used in official national accounts such as the UNSNA, NIPAs and the European System of Accounts (ESA) since the 1930s. Statistically it is a measure of gross net investment (acquisitions less disposals) in fixed capital assets by enterprises, government and households within the domestic economy, during an accounting period such as a quarter or a year.

countries with a high level of information technology are more likely to apply IT in construction than the countries with a low level of information technology.

3.1.2 Labor Productivity Measurement

Since direct construction productivity measurement is hard to be found for every selected country, the author calculates labor productivity as the construction value added per hour worked, which are available in the GGDC database. Value added is the gross output of an industry or a sector less its intermediate inputs, representing the contribution of an industry or sector to gross domestic product (GDP). Value added by industry can also be measured as the sum of compensation of employees, taxes on production and imports less subsidies, and gross operating surplus. Table 3.1 summarizes the national agencies responsible for value added as well as GDP measurement for the 17 countries selected in this research.

Table 3.1: National Agencies Responsible for Value Added Measurement

Country	Agency
Australia	Australian Bureau of Statistics
Austria	Statistik Austria
Canada	Statistics Canada
Denmark	Danmarks Statistik
Finland	Tilastokeskus
France	Institut National de la Statistique et des Etudes Economiques
Germany	Statistisches Bundesamt
Greece	National Statistical Service of Greece
Ireland	Central Statistics Office Ireland
Italy	Istituto Nazionale di Statistica
Japan	Ministry of Economy, Trade and Industry
Netherlands	Centraal Bureau voor de Statistiek
Portugal	Instituto Nacional de Estatística
Spain	Instituto Nacional de Estadística
Sweden	Statistiska Centralbyrån
UK	UK Statistics Authority, Office for National Statistics
United States	Bureau of Economic Analysis

For each of the sampled countries, the author collected value added in its current currency, value added deflator (equal to 100 in 1995) and total hours worked in the construction sector. Then, the labor productivity in year T was calculated through the following equation 3.1:

$$Labor\ Productivity = \frac{Value\ Added\ in\ Year\ T}{Total\ Hours\ Worked\ in\ Year T} \times \frac{100}{ValueAdded\ Deflator\ in\ Year\ T} \tag{3.1}$$

3.1.3 Analysis Approach

First, the author analyzed the trend of construction productivity in the sampled countries. Next, the author identified the trend of ICT investment in these countries. Then, the author observed if the large construction productivity improvement happened in the countries with large ICT investment or investment improvement. As examined by others (Brynjolfsson 1993), IT investments can require a longer term of around five to fifteen years before the full benefit of the investment is realized, therefore, the authors investigated productivity improvement from 1980 to 2003 (according to data's availability) and ICT investment from 1980 to 2000.

3.2 Industry-level Analysis

The purpose of this analysis is to compare the U.S. construction industry with other U.S. industries with respect to the relationship between the IT industry's contribution and productivity. This analysis also tested if the industries with high IT contribution were associated with quicker productivity improvement. The data used in this section was also from The Groningen Growth and Development Centre (GGDC).

3.2.1 Productivity Measurement

In this section, the author compared the productivity improvement across US industries rather than the productivity itself, therefore a volume instead of value index of productivity measurement is used. The productivity in a certain year is defined as the relative gross value added per hour worked to the year of 1995 (Equation 3.2).

$$Labor\ Productivity = \frac{VA\ in\ Year\ T}{Total\ Hours\ Worked\ in\ Year T} \times \frac{100}{VA\ Deflator\ in\ Year\ T} \times \frac{Total\ Hours\ Worked\ in\ 1995}{VA\ in\ 1995}$$

(3.2)

In this equation, VA means the gross value added in current dollar of a certain industry in a certain year, and for any industry the labor productivity in 1995 is equal to 100.

3.2.2 ICT Contribution Measurement

In this research, the author used the contribution of ICT capital to gross value added growth (percentage points) in an industry to measure the IT contribution. The composition of Gross Value Added Growth is shown in the following Equation 3.3.

$$VA = L + KIT + KNIT + MFP \tag{3.3}$$

In Equation 3.3, VA denotes the gross value added growth, L denotes the contribution of labor input growth, KIT denotes the contribution of ICT capital, KNIT denotes the contribution of Non-ICT capital and MFP denotes the contribution of multi-factor productivity growth. GGDC provided all of these measurements in its KLEM database.

3.2.3 Analysis Approach

First, the author analyzed the productivity trend and ICT contribution trend in the U.S. construction industry followed by analysis of the two trends for all US industries. This would find the construction industry's position in the US total industry regarding productivity and ICT contribution. Finally, the author tested if the industries with higher ICT contribution experienced quicker productivity improvement. Since ICT contribution may change quickly in an industry, which means in one period it can be lower, but in another period it may be very high, the author tested the relationship between productivity improvement and average ICT contribution in a relatively short period (five years). According to the data's availability, the author conducted the analysis for 1980 to 2005.

3.3 Project-level Analysis

The purpose of this analysis is to identify the relationship of automation and integration technology usage on work functions/ tasks in construction projects, and thus provide a clear picture with respect to the association between construction labor productivity and automation/integration usage.

The data source is the CII Benchmarking & Metrics (BM&M) dataset. The dataset includes 86 projects, providing data on unit rate productivity performance and automation/integration use of various work functions. According to the installed cost, the projects are grouped to large projects (installed cost not less than 5 million dollars) and small projects (installed cost less than $ 5 million dollars), and CII Benchmarking & Metrics program collected the data through two different questionnaires (Appendix A and B, only the content related to this research were cited). For large projects and small projects, the unit rate productivity metrics are the same, but the work functions used to evaluate automation and integration use are different. Unit rate productivity metrics are presented in Table 3.2. The productivity data is provided from three levels: discipline level, subcategory level and element level. Because of the limitation of data availability, only unit rate productivity data in the following four trades are used in this research: concrete, structural steel, electrical and piping. For electrical and piping, there are no discipline-level data available.

Table 3.2: BM&M Database Productivity Metrics

Major Categories	Discipline Level	Subcategory Level	Element Level
	Description	Description	Description
Concrete	Total Concrete	Total Slabs	On-Grade
			Elevated Slabs/On Deck
			Area Paving
		Total Foundations	< 5 cubic yards
			5~20 cubic yards
			21~50 cubic yards
			> 50 cubic yards
		Concrete Structures	
Structural Steel	Total Structural steel	Structural Steel	
		pipe racks & Utility Bridges	
		Miscellaneous Steel	
Piping		Total Small Bore	Carbon Steel
			Stainless Steel
			Other Alloys
		Total Large Bore (ISBL)	Carbon Steel
			Stainless Steel
			Other Alloys
		Total Large Bore (OSBL)	Carbon Steel
Electrical		Total Electrical Equipment	Panels and Small Devices
			Electrical Equipment 600V & Below
			Electrical Equipment Over 600V
		Total Conduit (LF)	Exposed or Aboveground Conduit (LF)
			Underground, Duct Bank or Embedded
		Cable Tray (LF)	
		Total Wire and Cable	Power and Control Cable - 600V & below(LF)
			Power Cable 5 & 15KV (LF)
		Lighting (each-Fixtures)	
		Grounding (LF)	
		Electrical Heat Tracing (LF)	

Note: the blank blue cells indicate productivity data is not available.
Source: CII BM&M database.

3.3.1 Productivity Definition and Normalization

The labor productivity in the project-level analysis is unit rate productivity, which is defined as the actual work hours per installed quantity, e.g. work hours per ton of structural steel installed (Equation 3.4).

$$\text{Unit Rate Productivity} = \frac{\text{Actual Work Hous}}{\text{Quantity Installed}} \qquad (3.4)$$

It is important to note that a lower productivity number per equation 3.4 is better. To ensure company confidentiality and allow comparisons across different tasks and trades, the raw unit rate productivities were normalized using the Min-Max method (Indovina et al., 2003) based on the following Equation 3.5:

$$P_{norm} = \frac{P_{raw} - P_{raw\min}}{P_{raw\max} - P_{raw\min}}(P_{norm\max} - P_{norm\min}) + P_{norm\min} \tag{3.5}$$

In equation 3-2, P_{norm} is the normalized unit rate productivity, P_{raw} is the raw unit rate productivity measure, $P_{raw\min}$ and $P_{raw\max}$ are the minimum and maximum raw unit rate productivity values in the category, $P_{norm\min}$ and $P_{norm\max}$ are the minimum and maximum normalized unit rate productivity values, equal to 1 and 10, respectively. The normalized productivity is consistent with raw productivity measure, a lower value indicating better productivity.

3.3.2 Outliers Identification

Before the raw productivity data is normalized, extreme outliers in the BM&M productivity dataset should be identified and removed. To be systematic in identifying the outliers, box plots were used, which use a two-stage flagging process for identifying the outliers as shown in figure 3.1. In this figure, the lower quartile has 25% of the sample values below it and 75% above. The upper quartile has 25% of the sample values above it and 75% below. The middle half of the sample lies between the upper and lower quartile. The distance between the upper and lower quartile is called the interquartile range, which is also called box length.

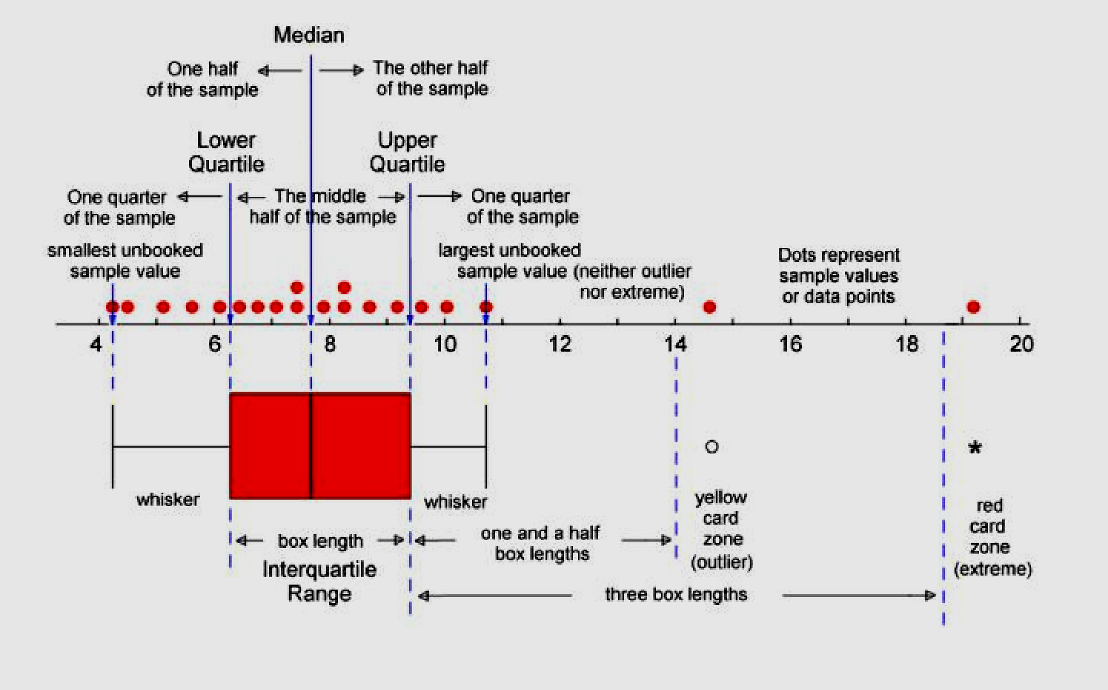

Figure 3.1: Box Plot Example

Using a conventional technique of identifying extreme outliers, values more than three box lengths from either end of the box will receive an automatic red card, an indicator of an extreme outlier. For each unit rate productivity data point in the red-card zone, the researchers examined other productivity measures reported by the same project. If many other unit rate productivity measures from the same project are also found to be extremely large or small, all data from the corresponding project were removed. In addition to examining other unit rate productivity measures associated with each outlier, the researchers examined the associated technology use level reported on the project. If the productivity and the technology use level indicate a strong negative relationship, i.e., the productivity was extremely small (please note in this case, a smaller unit rate productivity measure is favorable), but the technology use was also extremely low, or vice-versa, data from the project were also removed.

3.3.3 Work Functions

To assess the automated and integrated information systems on construction jobsites, the author examined the level of automation and integration that projects have achieved in the following work functions, established by Kang et al. (2006):

For large projects, 13 work functions were identified:

- Business planning & analysis: instituting a set of business goals with the project, explaining the reasons why the goals are believed attainable, and planning to reach those goals;
- Conceptual definition & design: the stage in the life of a project that culminates in the preparation of a document containing a functional program, an architectural or spatial program, a concept estimate and a set of design standards;
- Project definition & facility design: mission statement and overall scope of a project, including scope of constructed environment, e.g. buildings, structures, infrastructure, plant and equipment;
- Supply management: managing the methods and processes of acquiring materials, goods, or services, etc, and administering the relationship with suppliers;
- Project management: planning organizing, and managing resources to bring about the successful completion of specific project goals and objectives;
- Offsite/pre-construction: the use of modularization and prefabrication;
- Construction: all the work involved in assembling resources and putting together the materials required to form a new or changed facility;
- As-built documentation: documenting drawings and diagrams that provide an accurate representation of how the product or facility is actually built;
- Facility start-up & life cycle support: the activities facilitate the transitional phase between plant construction completion and commercial operations, and the phases of operation and disposal.

Project management, due to its importance in the project execution process, was further subdivided into five work functions, bringing the total number of work functions examined in this study to 13.

- Coordination system: the system linking various areas of a project to ensure the transfer of information or hardware at interface points at the appropriate times, and the identification of any further necessary resources;

- Communications system: the system transmitting and validating receipt of information to make the recipient understand what the sender intends, and to assure the sender that said intent is understood;
- Cost system: a project-cost accounting system of ledgers, asset records, liabilities, write-offs, taxes, depreciation expense, raw materials, pre-paid expenses, salaries, etc.
- Schedule system: the system managing or rearranging of the activities in a project schedule to improve the outcome based on the latest available information; and
- Quality system: the system for maintaining quality requirements in a product or project.

For small project, only five work functions were identified:

- Detailed design: the part of a project life cycle during which working drawings, standards, specifications and tender documents are prepared. This phase is over when all approved drawings and specifications for construction (or last package for fast-track) are released;
- Procurement: a process for establishing contractual relationships to accomplish project objectives. The assembly, tendering and award of contracts or commitment documents;
- Construction: all the work involved in assembling resources and putting together the materials required to form a new or changed facility;
- Maintenance: upkeep of property, equipment, or conditions (such as working conditions);
- Project management (including control): planning, organizing, and managing resources to bring about the successful completion of specific project goals and objectives.

3.3.4 Automation and Integration Use Level

For the purpose of this research, the author adopted the following definitions of automation and integration as developed by O’Connor and Yang (2004).

- ***IT Automation*** is defined as the use of an electronic or computerized tool by a human being in order to manipulate or produce a product. Hard automation, such as robotics, is not included in this definition.
- ***IT Integration*** is defined as the sharing of information between project participants or melding of information sourced from separate systems.

Using scales developed by previous research efforts (Kang et al., 2006), the levels of automation and integration of the systems that control the above work functions were based on the following five-point scale:

Automation Levels:

- Level 1(None/Minimal): little or no utilization beyond e-mail.
- Level 2 (Some): “Office” equivalent software, 2D CAD for detailed design.
- Level 3 (Moderate): standalone electronic/automated engineering discipline (3D CAD) and project services systems.
- Level 4 (Nearly full): Some automated input/output from multiple databases with automated engineering discipline design and project services systems.
- Level 5 (Full): fully or nearly fully automated systems dominate execution of all work functions.

Integration Levels:

- Level 1(none/minimal): little or no integration of electronic systems/applications.
- Level 2 (some): manual transfer of information via hardcopy of email.
- Level 3 (moderate): manual and some electronic transfer between automated systems.
- Level 4 (nearly full): most systems are integrated with significant human intervention for tracking inputs/outputs.
- Level 5 (full): all information is stored on a network system accessible to all automation systems and users. All routine communications are automated. The automated process and discipline design systems are fully integrated into 3D design, supply management, and project services systems (cost, schedule, quality, and safety).

The above definition levels were used to assess the level of automation and integration achieved by projects in specific work functions. It should be noted that these data are self-reported by company participants and are therefore subject to some level of interpretation and possibly less credibility than what might have been achieved as a result of researcher site visits to each project and company. The trade-off is that much more data are available than what would have been affordable in a site-visit approach.

For the purposes of the analyses, projects scoring above the overall median among the sampled project were classified as having a high level of automation or integration on a certain work function, and projects scoring below the median were defined as having a low level of automation or integration on the work function. The reason for using the median rather than the mean is that automation and integration levels do not have a perfectly normal distribution.

3.3.5 *t*-test on Each of the Work Functions

For each work function, the author calculated the average normalized unit rate productivities for the projects with high and low automation (or integration) use levels on this work function, and then compared them to see if there was significantly positive difference. The null and alternative hypotheses are as followings:

H_0: $P_H = P_L$

H_1: $P_H < P_L$

where P_H denotes the average productivity with high-level automation (or integration) usage on a certain work function and P_L denotes the average productivity with low-level automation (or integration) usage on a certain work function.

This test was performed with SPSS. Although significance at the 95% confidence level is widely accepted in scientific research, considering the low sample size, significance at 90% and 85% were also presented for reference.

3.3.6 *t*-test on Automation or Integration Index

The purpose of this analysis is to investigate the general relationship between automation and integration usage to unit rate productivity. In other words, through this analysis the researcher wants to examine a larger picture about the relationship rather than a smaller picture on each of the work functions.

An automation and an integration index were calculated (ranging from 0 to 10) based on the all work function automation and integration use levels. For purposes of the analyses, projects scoring 5 percent above the overall median among all sampled projects were classified as having a high level of automation or integration, and projects scoring 5 percent below the median were defined as having a low level of automation or integration. The purposes of using such a 5% range below and above the median are: (1) to create two groups with more distinct differences in automation and integration use levels; and (2) to guarantee that the sample sizes are large enough to perform the statistical analyses. The authors acknowledge that the differences in technology use levels would be larger by using a wider range, such as 10% below and above the median, but the sample sizes would be too small to conduct the analyses. By using a 5% percentage above and below the median, the writers can reach a balance between the technological difference of the two groups and the sample size. Once again, the *t*-test was used to test the difference in normalized unit rate productivities between the two groups.

The method of calculating the automation and integration indices are similar to that developed by O'Connor and Yang (2004). The procedure uses the following steps:

- For each work function, transfer automation (integration) use level 1, 2, 3, 4, and 5 to automation (integration) use score 0, 0.25, 0.5, 0.75 and 1;
- Calculate the mean automation(integration) use score of all work functions for each project;
- Use a 10-point index:

$$\text{Automation (Integration) Index} = \text{Mean Automation(Integration) Use Score} \times 10 \quad (3.6)$$

The generalized equations are:

$$\text{Automation Index} = \text{Mean (Work function automation use level-1)} \times 2.5 \quad (3.7)$$

$$\text{Integration Index} = \text{Mean (Work function integration use level-1)} \times 2.5 \quad (3.8)$$

An Automation Index example calculation is shown in Table 3.3.

Table 3.3: Automation Index Example Calculation

	Automation Use Level					
Work Function	1	2	3	4	5	Score
Business planning & analysis	0	0.25	0.5	0.75	1	0.5
Conceptual Definition & design	0	0.25	0.5	0.75	1	0.5
Project (discipline) definition & facility design	0	0.25	0.5	0.75	1	0.5
Supply Management	0	0.25	0.5	0.75	1	0.75
Coordination System	0	0.25	0.5	0.75	1	0.5
Communications System	0	0.25	0.5	0.75	1	0.5
Cost System	0	0.25	0.5	0.75	1	0.75
Schedule System	0	0.25	0.5	0.75	1	0.75
Quality System	0	0.25	0.5	0.75	1	0.5
Offsite/pre-construction	0	0.25	0.5	0.75	1	0.5
Construction	0	0.25	0.5	0.75	1	0.25
As-built documentation	0	0.25	0.5	0.75	1	0.5
Facility Start-up & life cycle Support	0	0.25	0.5	0.75	1	1
Total						7.5
Average						0.5769
Automation Index=Average×10						5.769

Note: The numbers in the shaded cells are automation use scores transferred from corresponding automation use levels on each work function in a project.

3.3.7 Actual Unit Rate Productivity Comparison

The described *t*-test results were based on normalized unit rate productivity measures in order to preserve the confidentiality of the CII BM&M data and allow analysis across different tasks and trades, since the normalized unit rate productivity measures were dimensionless. However, reporting the analyses using normalized productivity obscured the actual effects. To help clarify the results, the author calculated the means of raw unit rate productivity for the projects with high-level and low-level technology use, and then calculated the percentage difference with the following Equation 3.9:

$$Percentage\ Difference\ of\ Unit\ \ Rate\ Productivity = \frac{(Mean\ P_{RawL}\ \text{-}\ Mean\ P_{RawH}\ )}{Mean\ P_{RawL}} \times 100$$

(3.9)

where P_{RawH} denotes the raw unit rate productivity with high-level automation (or integration) index. Similarly, P_{RawL} denotes the raw unit rate productivity with low-level automation (or integration) index. According to Equation 3.9, the unit rate productivity is measured as actual work hours per installed quantity, so the percentage difference of unit rate productivity means the percentage of time savings per installed quantity when using a high versus a low level of technology usage.

It is emphasized that the work functions presented in actual unit rate productivity comparisons were consistent with those in *t*-test results. Therefore, after understanding which work functions were significantly related to either automation or integration technologies, the author could also quantify the actual effects. The calculation procedure is as the following:

(1) Based on the *t*-test results, select the work functions that are needed to be presented in actual unit productivity comparison.

(2) For the selected work functions, calculate each of the mean unit rate productivity at the subcategory level for low- and high-level technology uses, respectively.

(3) Calculate each of the percentage differences of unit rate productivity at the subcategory level.

(4) Percentage difference of unit rate productivity in one trade = the average of percentage difference of unit rate productivity at the subcategory level.

The following is a calculation example about Automation Use in the concrete trade:

Table 3.4: Actual Unit Rate Productivity Comparison Example (Concrete/Automation)

Work function	Productivity	High level Automation	Low level Automation	Percentage Difference
Schedule System	Slab (hr/cy)	6.150	13.055	52.9%
	Foundation (hr/cy)	11.178	15.534	28.0%
	Concrete Structure (hr/cy)	13.547	29.676	54.4%
	Concrete Trade Average:			**45.1%**
Quality System	Slab (hr/cy)	6.558	13.640	51.9%
	Foundation (hr/cy)	16.287	17.959	9.3%
	Concrete Structure (hr/cy)	19.167	37.258	48.6%
	Concrete Trade Average:			**36.6%**

The result of Table 3.3 can be presented as follows:

The projects with a high-level automation use on Schedule System associated with an average 45.1% greater productivity in the concrete trades than the projects with a low-level automation use.

The projects with high-level of automation use on Quality System associated with an average 36.6% greater productivity in the concrete trades than the projects with low-level automation use.

3.3.8 Identifying the Latent Factors

The purpose of this factor analysis is to discover simple patterns of relationships among the 13 work functions of large projects. In other words, it seeks to discover if the work functions can be explained largely or entirely in terms of a much smaller number of variables. In this research, the authors used the principal factor analysis (PFA) to perform the factor analysis and generate the latent factors.

Factor analysis was just an intermediate step in this research, and a multiple-regression model was built to relate the latent factors to the normalized unit rate productivity as shown in Equation 3.10. The result of the model provided the relative importance of the latent factors.

$$NormProdictivity = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \tag{3.10}$$

Where Norm Productivity denotes normalized unit rate productivity, $\alpha, \beta_1, \beta_2, \cdots, \beta_k$ denotes parameters and $x_1, x_2 \cdots, x_k$ denote the latent factors identified through factor analysis.

The detailed processes of factor analysis and multiple regression model were described in the following section: data analysis methods.

3.4 Data Analysis Methods

The major data analysis method in this research includes independent sample *t*-test, spearman rank correlation, factor analysis and multiple regression analysis.

3.4.1 Independent Sample *t*-test with Levene's Test for Equality of Variances

Independent sample *t* test examines the mean of a single variable in one group differs from that in another. This test can be used when it assumes that the two distributions have the same variance or different variances.

When the same variance assumed, the *t* statistic to test whether the means are different can be calculated as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{X_1X_2} \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{3.11}$$

where

$$S_{X_1X_2} = \sqrt{\frac{(n_1 - 1)S_{X_1}^2 + (n_2 - 1)S_{X_2}^2}{n_1 + n_2 - 2}}. \tag{3.12}$$

When the two population variances are assumed to be different (the two sample sizes may or may not be equal), the *t* statistic to test whether the population means are different can be calculated as follows:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{s_{\overline{X}_1 - \overline{X}_2}} \tag{3.13}$$

where

$$s_{\overline{X}_1 - \overline{X}_2} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}. \tag{3.14}$$

In the above four equations:

$\overline{X}_i$ =mean of group *i*;

n_i=number of observations in group *i*;

s_i^2=sample variance in group *i*.

In statistics, Levene's test is an inferential statistic used to assess the equality of variances in different samples. Some common statistical procedures assume that variances of the populations from which different samples are drawn are equal. Levene's test assesses this assumption. It tests the null hypothesis that the population variances are equal. If the resulting *p*-value of Levene's test is less than some critical value (typically 0.05), the obtained differences in sample variances are unlikely to have occurred based on random sampling. Thus, the null hypothesis of equal variances is rejected and it is concluded that there is a difference between the variances in the population. One advantage of Levene's test is that it does not require normality of the underlying data. Levene's test is often used before a comparison of means. When Levene's test is significant, modified procedures are used that do not assume equality of variance. In SPSS, the independent *t*-test is associated with Levene’s test. When running *t*-test, SPSS also runs the Levene’s test, and produces two values of *t* statistic and the corresponding *p*-values with and without the assumption of equal variance. Users can determine which *t* statistic and the corresponding *p*-value should be used based on the *p*-value of Levene's test.

A disadvantage of *t*-test is that the number of needed pair comparisons (*t*-tests) accelerates when the number of groups grows. Therefore, the *t*-test is not the efficient answer when the groups are large. In this case, ANOVA can be used to examine whether the variation between several groups is "significant". ANOVA puts all the data into one analysis and provides one number (*F*[4]) and one *p-value* for the null hypothesis. However, ANOVA is a procedure which typically assumes homogeneity of variance. Therefore, when this assumption cannot be satisfied and the number of groups is not more than two, the independent *t* test is a better choice.

For both *t*-test and ANOVA, one assumption is the data following normal distribution. However, when the sample size is large (more than 30), this assumption is not too strict.

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[4] The F statistic is aimed to test the hypothesis, $H_0: \mu_1 = \mu_2 = \cdots = \mu_k$
where μ_j is the mean of group *j*.
the F statistic is computed by the equation:

$$F = \frac{variantion\ among\ the\ sample\ means}{variation\ within\ the\ samples} = \frac{MS_B}{MS_W}$$

where $MS_B = \frac{SS_B}{df_B} = \frac{\sum_j n_j \left(\bar{y}_j - \bar{y}_{..}\right)^2}{(k-1)}$ and $MS_W = \frac{SS_W}{df_W} = \frac{\sum_{ij}\left(y_{ij} - \bar{y}_j\right)^2}{\sum_j \left(n_j - 1\right)}$

3.4.2 Spearman Rank Correlation

Spearman rank correlation measures the strength of the relationship between variables. It is usually a substitute of Pearson correlation when identifying the non-linear relationship. The nonparametric Spearman correlation is based on ranking the variables, and it makes no assumption about the sample distribution.

In this research, Spearman rank correlation coefficient[5] was computed to examine the relationship of construction labor productivity and information and communication technology (ICT) investment across the sampled countries. After descriptive analyses generated the labor productivity improvement and ICT investment improvement, the countries were ranked twice based on the two improvements respectively, with the highest improvement getting a value of 1. The countries with the same improvement value each received the average rank they would have received. The Spearman rank correlation coefficient (r) gives an indication of the strength of relationship. In general, $r > 0$ indicates positive relationship, $r < 0$ indicates negative relationship while $r = 0$ indicates no relationship (or that the variables are independent and not related). Here $r = +1.0$ describes a perfect positive correlation and $r = -1.0$ describes a perfect negative correlation. Closer the coefficients are to +1.0 and -1.0, greater is the strength of the relationship between the variables.

3.4.3 Factor Analysis

Factor analysis is a statistical technique to identify the latent factors explaining the correlation between the observed variables (Loehlin 1998). In other words, factor analysis reveals simple patterns of relationships among the observed variables.

Typically factor analysis consists of two steps, factor extraction and rotation. Both principal component analysis (PCA) and exploratory factor analysis (also named as principal factor analysis, PFA) can be used to reduce the dimension of multivariate data, but PFA is more concerned with identifying the latent variables which presents the underlying structure of the observed variables. PFA assumes that the variance of a single

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[5] the Spearman rank correlation coefficient is defined by

$$\rho = 1 - 6 \times \sum_{i=1}^{n} \frac{d_i^2}{n \times (n^2 - 1)}$$

where d_i is the difference of the rank of factor *i* between the two groups.

variable has two contributing sources of variation, common variance that is shared by other observed variables, and unique variance that is unique to a particular variable and includes the error component. PFA analyzes only the common variance of the observed variables. PCA considers the total variance and makes no distinction between common and unique variance. PFA is preferred if the explicit assumptions of the measurement model are appropriate (Costello and Osborne 2005; Lattin et al 2003). Therefore, this research chose PFA to identify the underlying structure of the construction project work functions. SPSS provides six PFA options: unweighted least square[6], generalized least squares[7], maximum likelihood[8], principal axis factoring[9], alpha factoring[10], and image factoring[11] (SPSS 2009). Generally, maximum likelihood and principal axis factoring could provide the best results (Costello and Osborne 2005). Maximum likelihood is the best choice when the data come from a multivariate normal distribution because it calculates a wide range of indexes of the goodness of fit of the model and allow statistical significance testing of factors loadings and correlations among the latent factors and the calculation of confidence intervals (Costello and Osborne 2005). Alternatively if the data violate the presumption of multivariate normality, principal axis factors is recommended.

When extracting the variables, one question is how many latent factors should be retained for rotation. Fewer latent factors could simplify the results and interpretation, but more latent factors will keep more information and variance of the observed variables. The default option in SPSS is based on the Kaiser rule to drop all latent factors with

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[6] Unweighted Least Squares Method minimizes the sum of the squared differences between the observed and reproduced correlation matrices ignoring the diagonals (SPSS 2009).

[7] Generalized Least Squares Method minimizes the sum of the squared differences between the observed and reproduced correlation matrices. Correlations are weighted by the inverse of their uniqueness, so that variables with high uniqueness are given less weight than those with low uniqueness (SPSS 2009).

[8] Maximum likelihood produces parameter estimates that are most likely to have produced the observed correlation matrix if the sample is from a multivariate normal distribution. The correlations are weighted by the inverse of the uniqueness of the variables, and an iterative algorithm is employed (SPSS 2009).

[9] Principal axis factoring extracts factors from the original correlation matrix with squared multiple correlation coefficients placed in the diagonal as initial estimates of the communalities. These factor loadings are used to estimate new communalities that replace the old communality estimates in the diagonal. Iterations continue until the changes in the communalities from one iteration to the next satisfy the convergence criterion for extraction (SPSS 2009).

[10] Alpha considers the variables in the analysis to be a sample from the universe of potential variables. It maximizes the alpha reliability of the factors (SPSS 2009).

[11] Image factoring is developed by Guttman and based on image theory. The common part of the variable, called the partial image, is defined as its linear regression on remaining variables, rather than a function of hypothetical factors (SPSS 2009).

eigenvalues[12] under 1.0. However, the Kaiser rule is considered among the least accurate methods for determining the number of latent factors to retain (Costello and Osborne 2005). Another widely used option is the screeplot, which plots the eigenvalues as the vertical axis in a decreasing order and the corresponding latent factors as the horizontal axis (Figure 3.2). Theoretically, the plot shows a distinct break ("elbow") between the steep slope of the eigenvalues and the gradual trailing of the scree (SPSS 2009). The number of data points above the "elbow" is usually the number of the latent factors to retain (Costello and Osborne 2005). In this research, both methods were considered when deciding the number of latent factors.

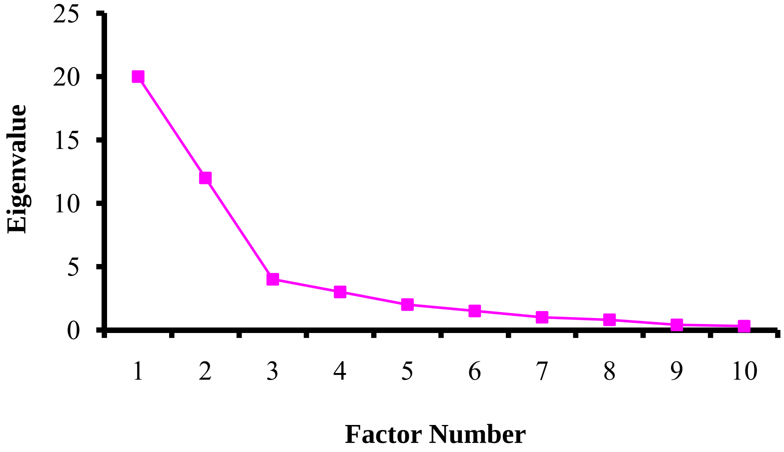

Figure 3.2: Sample Scree Plot

Rotation is a process of adjusting the factor axes to achieve a simpler and pragmatically more meaningful factor solution. Specifically, rotation serves to transform the models and retain the same number of factors, but to improve them with respect to the interpretability. SPSS has five types of rotation option to help simplify and clarify the latent factor structure: *varimax*, *quartimax*, *equamax*, *direct oblimin* and *promax* (SPSS

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[12] Eigenvalue is the variance in a set of variables explained by a latent factor, and denoted by **lambda**. An eigenvalue is the sum of squared values in the column of a factor matrix, or

$$\lambda_k = \sum_{i=1}^{m} a_{ik}^2$$

where a_{ik} is the factor loading for variable i on factor k, and m is the number of variables. In matrix algebra the principal eigenvalues of a correlation matrix **R** are the roots of the characteristic equation.

2009). The first three are orthogonal methods, which generate uncorrelated latent factors, and the later two are oblique methods, which allow the latent factors to correlate. More often than not, researchers use orthogonal rotation because it generates more easily interpretable results. However, Costello and Osborne (2005) argued that in social science, behaviors are barely independent of each other, and oblique methods are better options.

Factor scores represent the location of each of the original observations in the reduced factor space. As a byproduct of factor analysis, factor scores are automatically generated for each latent factor in SPSS. The factor scores may be correlated even using orthogonal rotation methods. Since the factor score for each latent factor has different range, it is difficult to interpret the factor score. Maloney and McFillen (1985) simplified the factor scores by converting each factor score into its corresponding proportion of that factor's potential range. The methodology first computes the lowest possible and the highest possible score for each latent factor. Next, a factor scale score is calculated based on Equation 3.15. The factor scale score indicates how high the factor score is relative to its scale. The factor scale score represents the factor score uniformly, and therefore, the research could compare the latent factors across the various scales. In this research, in order to make the factor scale score consistent with the scale of automation and integration use level, the author normalized the factor scale score to a 1 to 5 scale through Equation 3.16.

$$Factor\ scale\ score = \frac{factor\ score - the\ lowest\ possible\ score}{the\ highest\ possible\ score - the\ lowest\ possible\ score} \tag{3.15}$$

$$Factor\ scale\ score = 1 + \frac{factor\ score - the\ lowest\ possible\ score}{the\ highest\ possible\ score - the\ lowest\ possible\ score} \times (5-1) \tag{3.16}$$

3.4.4 Multivariate Regression Analysis

Factor analysis was just an intermediate step in this research, and multiple regression analysis was used to explore the relationship between normalized unit rate productivity and the latent factors, in place of the automation and integration uses on the 13 work functions. A multiple regression analysis allows for determining the influence of each latent factor on construction project activity productivity.

As mentioned before, the regression model example is given by:

$$NormProdictivity = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \tag{3.10}$$

Where b_i, the regression coefficient for the corresponding independent variable x_i, may be conceived as the "potential influence" of x_i on dependent variable, *Y*. However, it is difficult to rank the independent variables directly based on the magnitude of the regression coefficients (b_i), since the independent variables (x_i) have different standard deviation, and are often in different units (Rosner 2000).

The standardized regression coefficient represents the average increase in dependent variable (expressed in standard deviation units of dependent variable) per standard deviation increase in the independent variable while controlling all other variables in the model. Therefore, the independent variable with a greater standardized regression coefficient is considered to have a stronger influence on the dependent variable. The standardized regression coefficient can be computed as the following equation:

$$b_i^s = \frac{b_i \times s_{x_i}}{s_y} \tag{3.16}$$

where b_i^s is the standardized regression coefficient for the *i*th variable. s_x is the corresponding standard deviation of the independent variable, and s_y is the standard deviation of the dependent variable.

R^2, the coefficient of determination, measure how much variation of the dependent variable is explained by the independent variables. Usually R^2 is considered as an indicator of how well a statistical model fits a set of observations. However, it should be noted that R^2 always increases when a new independent variable is added to the model. As a complement, the adjusted R^2 takes into account the number of independent variables and the number of observation included in a regression as Equation 3.17. The adjusted R^2 is a good benchmark for comparison when adding variables into the model in an attempt to improve the current model (Lattin et al 2003).

$$adjusted\ R^2 = R^2 - \frac{k-1}{n \times k} \times (1 - R^2) \tag{3.17}$$

where n=number of observations, and k=number of independent variables.

CHAPTER 4 : NATIONAL LEVEL ANALYSIS

4.1 Introduction of Data Source

The data used in this chapter are from Organisation for Economic Co-operation and Development (OECD) and The Groningen Growth and Development Centre (GGDC). OECD provided the Information and Communication Technology (ICT) investment as the percentage of non-residential gross fixed capital formation in each of the OECD countries in 1980, 1990 and 2000. From GGDC's 60-industry database the author collected data to calculate construction productivity in various countries. This database is a comprehensive internationally comparable dataset on industrial performance with annual numbers of value added, employment, hours and productivity for the OECD countries and Taiwan. This source was used since the data were classified according to the International Standard Industrial Classification (ISIC), which made industries comparable across countries. Due to the availability of data in both databases, 17 countries were included in analysis as follows: Australia, Austria, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, Portugal, Spain, Sweden, United Kingdom and United States.

For most variables and countries, the GGDC 60-Industry Database uses the OECD STructural ANalysis (STAN) database as the point of departure, which in turn is largely based on recent national accounts of individual OECD members. For example, OECD STAN database collected European countries' construction productivity data from Eurostat, which is the official statistical bureau of the European countries. For the United States, the construction productivity data is from U.S. Bureau of Economic Analysis (BEA), where the construction industry annual value added, the number of workers and the hour worked are available, and labor productivity can be calculated as the value added per worker or per hour. However, as discussed in Chapter 2 section 2.1, there were many concerns regarding the accuracy of these industry measures, particularly on the inflation indices used to measure construction industry real output. The concerns range from over reliance on the use of proxy inflation indices to deflate construction expenditures (Pieper 1990), the use of input cost inflation indices instead of the preferred output price indices (Dacy 1965, Gordon 1968, and Pieper 1990), and the challenge of measuring the change in the quality of industry output (Rosefielde and Mills 1979, Pieper 1990, Gullickson and Harper 2002). The cumulative effect of these concerns is that a productivity index does not exist for the U.S construction industry. Another result of these concerns is that the U.S. Census Bureau no longer maintains a constant dollar series of the Value of Construction Put in Place Statistics, which are the primary source of industry output measures. This is the reason that the GGDC 60-industry cannot obtain US construction productivity directly, but needs to develop it from the value added and the number of workers or hours worked. Although there are some inherent problems in using this aggregate measurement, previous research efforts have still used them to investigate construction productivity trends (Allen 1985, Teicholz 2001).

4.2 The Trend of Construction Productivity

The author investigated the trend of construction labor productivity through the percentage of productivity improvement between 1980 and 2003 (Equation 4.1).

$$\%\ Productivity\ Improvement = \frac{Productivity\ 03'\text{-}Productivity\ 80'}{Productivity\ 80'} \times 100\% \tag{4.1}$$

As shown in Figure 4.1, all of the sampled countries experienced an improvement on construction productivity from 1980 to 2003, except the United States with a 12.57% decrease. The average improvement in all of the 17 countries is 28.18%. Austria, United Kingdom and France experienced the most improvement by 76.78%, 69.54% and 49.54%, respectively. Except the United States, the countries experienced the least improvement on construction productivity were German (1.36 %), Japan (1.97%) and Canada (4.53%).

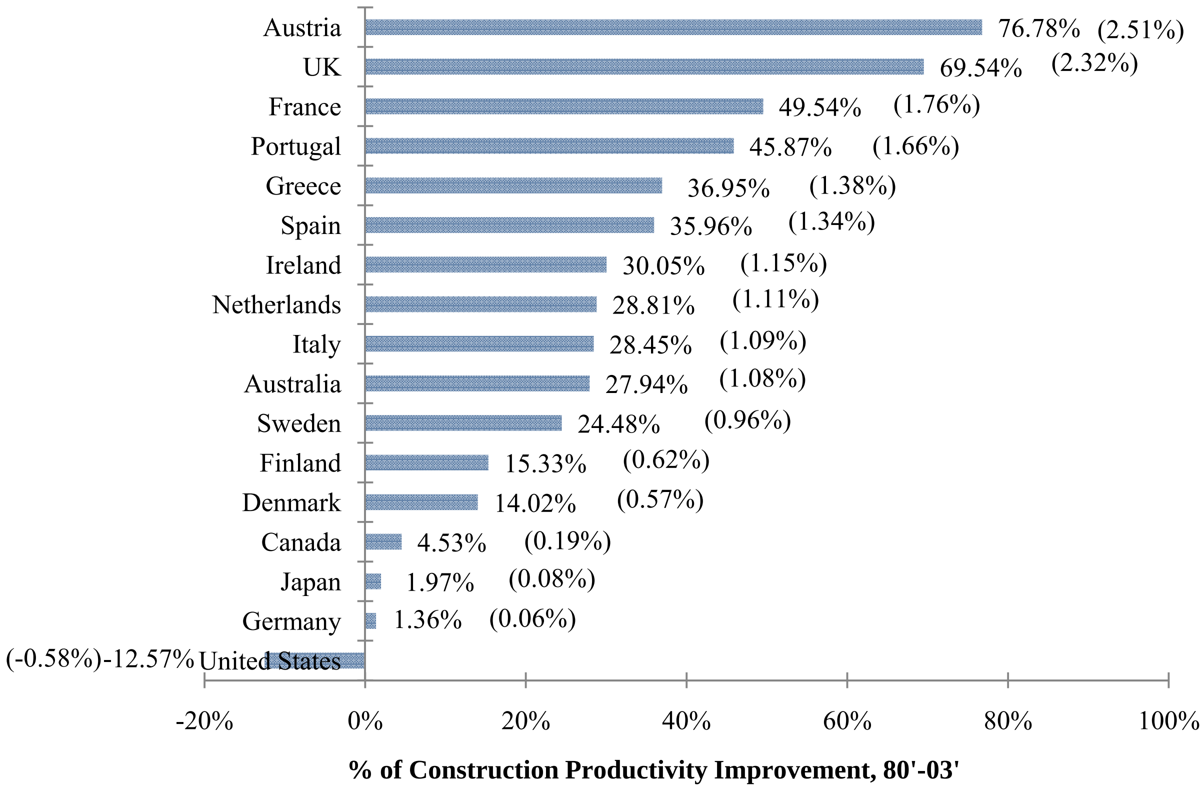

Figure 4.1: The Percentage of Construction Productivity Improvement, 80’-03’

Note: compound rates are shown in parentheses; Japanese data is from 1980 to 2002; data is from GGDC.

Besides the construction productivity trends in the overall 23 years period, the author also investigated the trend in two sub-periods:1980 to 1990 (Figure 4.2) and 1990 to 2003 (Figure 4.3). More details can be found from these analyses. In the decade of 1980 to 1990, there were three countries that experienced a decrease on construction labor productivity. Ireland experienced the largest decrease of 21.19%, followed by the United States (3.98%) and Canada (1.63%). Other 14 countries experienced an improvement on construction labor productivity in this period, ranging from 37.97% to 0.41%. Netherland, France and Japan experienced the most improvement by 37.97%, 35.28% and 34.55%, respectively. The average improvement in all of the 17 countries is 17.91%.

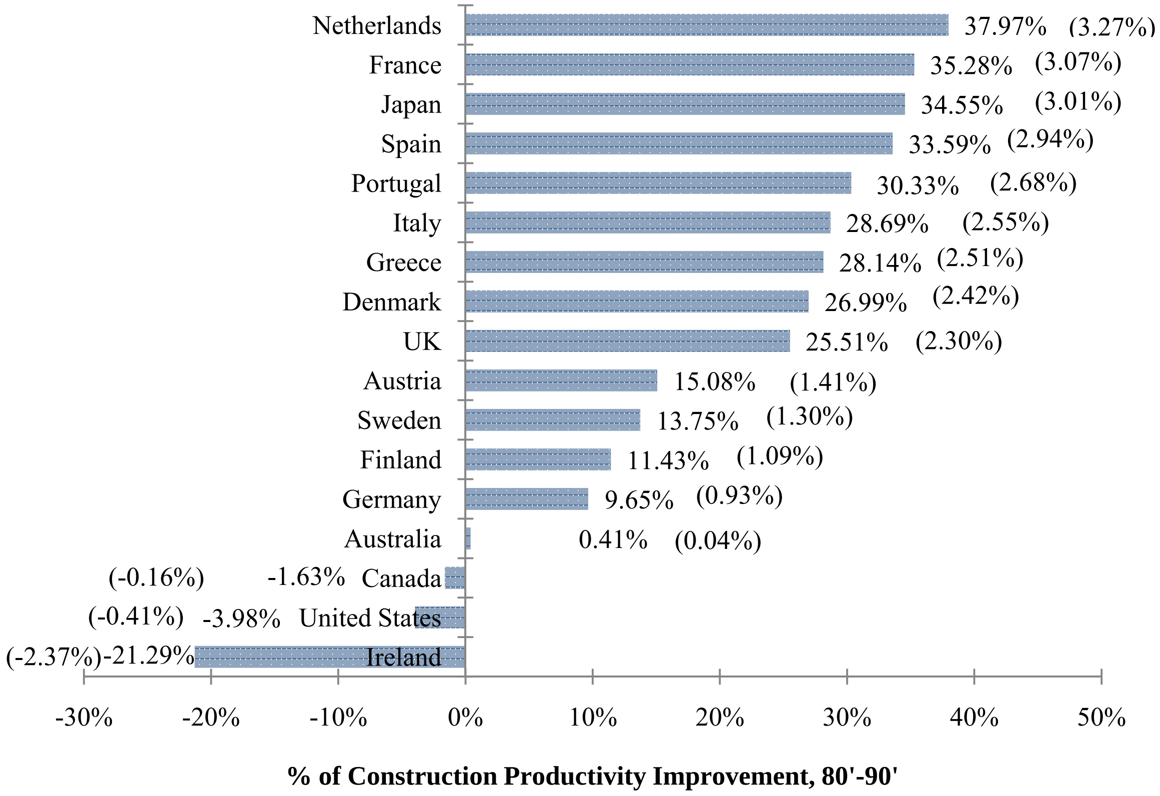

Figure 4.2: The Percentage of Construction Productivity Improvement, 80’-90’

Note: compound rates are shown in parentheses; data is from GGDC.

In the period of 1990 to 2003, there were 5 countries experienced a decrease on construction labor productivity. Japan experienced the most decrease by 24.21%, followed by Denmark (10.21%) and the United States (8.94%). The other two countries that experienced a decrease are Netherland and Italy by 6.64% and 0.19%, respectively. 12 countries experienced improvement on construction labor productivity. Ireland, Austria and UK experienced the most improvement by 65.23%, 53.62% and 35.09%, respectively. The average improvement in all of the 17 countries is 10.45%.

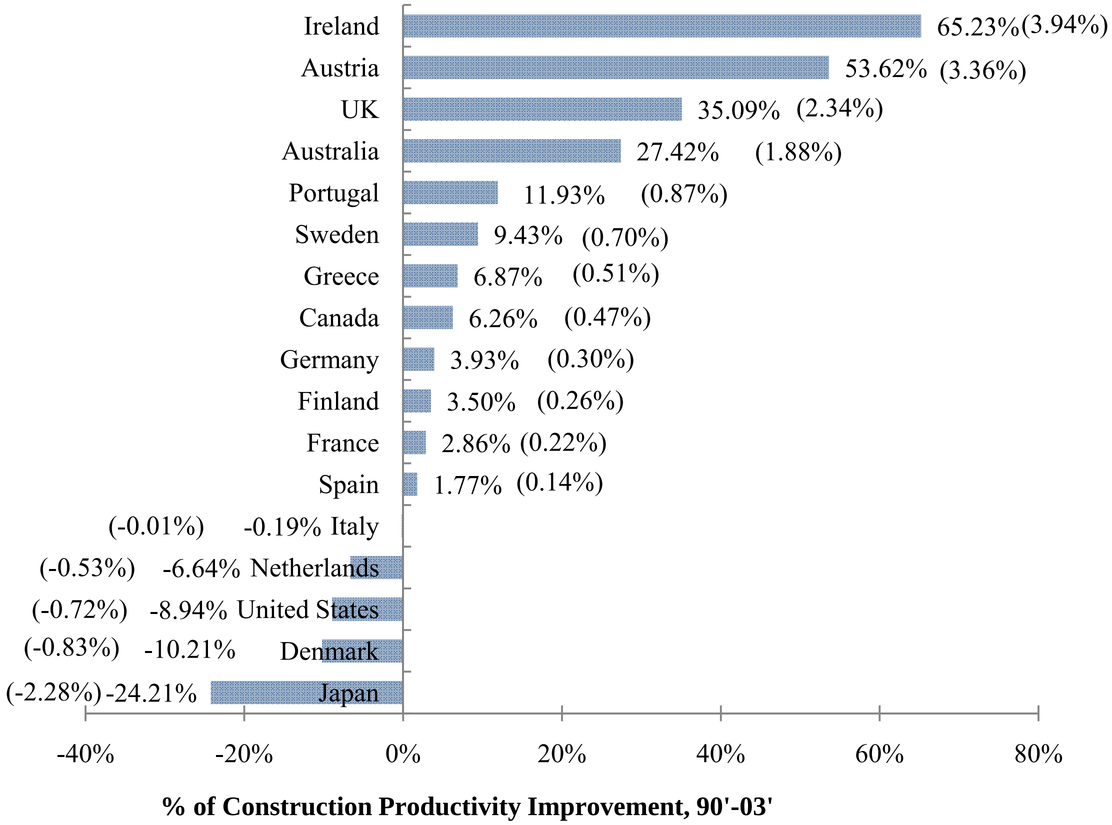

Figure 4.3: The Percentage of Construction Productivity Improvement, 90'-03'

Note: compound rates are shown in parentheses; Japanese data is from 1990 to 2002; data is from GGDC.

From Table 4.1, it can be observed that the United States experienced long-term decrease on construction labor productivity, which is consistent with the previous research (Teicholz 2000). In Denmark, Italy, Japan and Netherland, after ten years quick improvement, the construction productivity declined in the following 13 years, while in Ireland, the trend was opposite: after an obvious decrease in the period from 1980 to 1990, its productivity experienced a sharp improvement from 1990 to 2003. In United Kingdom the improvement rates were almost even in the two periods. Finland, France, Grace and Portugal seemed to have the similar patterns: their construction productivity experienced an improvement in the 23 years and the major improvement happened in the first 10 years. While Australia and Austria‘s construction labor productivity also experienced an improvement in the 23 years, the major improvement happened in the last 13 years.

Table 4.1: Construction Productivity Improvement Annual Compound Rate

Country	Construction Productivity Improvement Annual Compound Rate		
	1980'-1990'	**1990'-2003'**	**1980'-2003'**
Australia	0.04%	1.88%	1.08%
Austria	1.41%	3.36%	2.51%
Canada	-0.16%	0.47%	0.19%
Denmark	2.42%	-0.83%	0.57%
Finland	1.09%	0.26%	0.62%
France	3.07%	0.22%	1.76%
Germany	0.93%	0.30%	0.06%
Greece	2.51%	0.51%	1.38%
Ireland	-2.37%	3.94%	1.15%
Italy	2.55%	-0.01%	1.09%
Japan	3.01%	-2.28%	0.08%
Netherlands	3.27%	-0.53%	1.11%
Portugal	2.68%	0.87%	1.66%
Spain	2.94%	0.14%	1.34%
Sweden	1.30%	0.70%	0.96%
UK	2.30%	2.34%	2.32%
United States	-0.41%	-0.72%	-0.58%

Note: Japanese data is from 1980 to 2002; data is from GGDC.

4.3 The Trend of National ICT Investment

Next, the author identified the trend of national ICT investment. As mentioned in Chapter 3, the ICT investment in this dissertation denotes the percentage of ICT investment in none-residential gross fixed capital formation for the purpose of this research. The author calculated the percentage of ICT investment improvement between 1980, 1990 and 2000 through the following Equation 4.2.

$$\%\ ICT\ Investment Improvement = \frac{ICT\ Investment(year\ a) - Productivity(year\ b)}{Productivity\ (year\ b)} \times 100\% \qquad (4.2)$$

From 1980 to 2000, all of the 17 sampled country experienced remarkable growth on ICT investment (Figure 4.4). The average ICT investments are 7.3%, 12.3% and 18.7% in 1980, 1990 and 2000 respectively. In all of the three years, the United States had the largest percentage of ICT investment. In 1980, Greece had the lowest percentage of ICT investment, followed by Ireland and Sweden. In 1990, Ireland had the lowest percentage of ICT investment, followed by France and Greece. While in 2010, Spain had the lowest percentage of ICT investment, followed by Portugal and Austria.

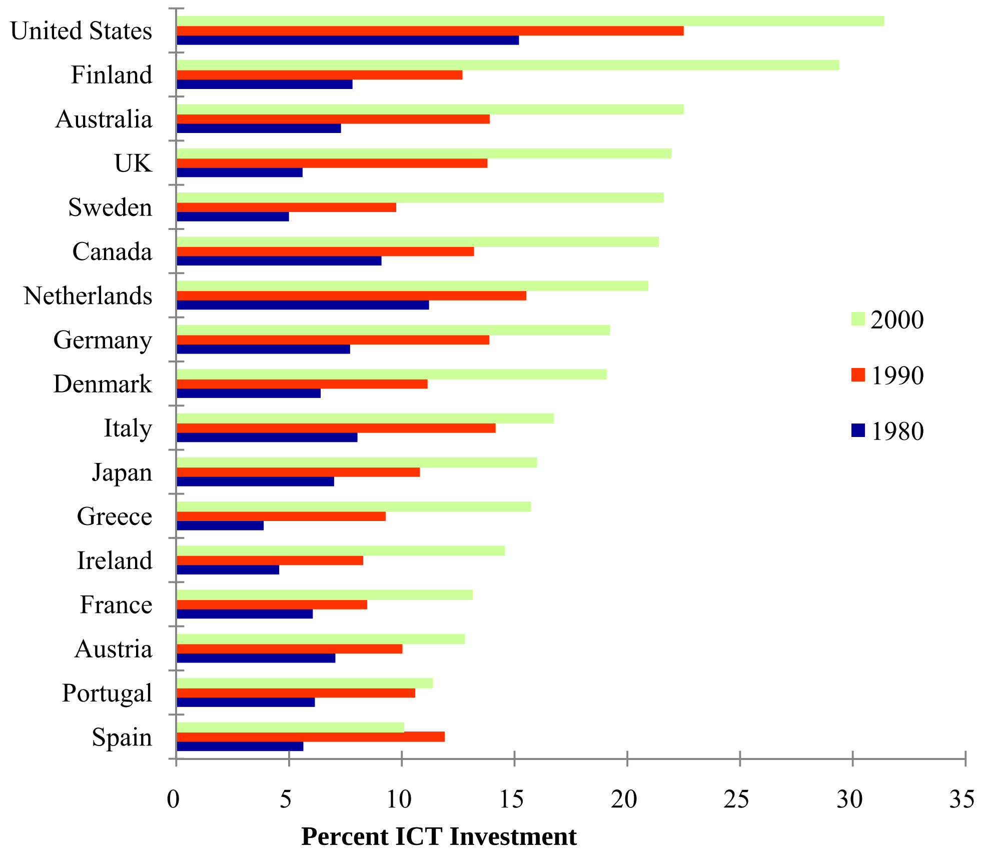

Figure 4.4: The National ICT Investment as a Percentage of Non-residential Gross Fixed Capital Formation

Note: data is from OECD.

In the 20 years, Sweden, Greece and United Kingdom experienced the largest improvement by 332.76%, 305.88% and 292.25%, respectively, while Spain, Austria and Portugal experienced the least improvement by 79.31%, 81.52% and 85.06%, respectively (Table 4.2). In the first decade (1980-1990), all of the 17 countries experienced remarkable ICT investment improvement, with an average of 76.34%. United Kingdom, Greece and Spain experienced the largest improvement, while Netherland, France and Austria had the least improvement. In the second decade (1990-2000), although except Spain all of the countries still had improvement on ICT investment, the average improvement (53.38%) was less than the first decade. Finland, Sweden and Ireland had the largest improvement, while Spain, Portugal and Japan had the least improvement.

Table 4.2: National ICT Improvement from 1980 to 2000

Country	ICT Investment Improvement		
	1980'-1990'	1990'-2000'	1980'-2000'
Australia	90.41%	61.87%	208.22%
Austria	42.15%	27.69%	81.52%
Canada	45.05%	62.12%	135.16%
Denmark	74.14%	71.31%	198.32%
Finland	62.43%	131.65%	276.27%
France	39.87%	55.27%	117.17%
Germany	80.16%	38.50%	149.53%
Greece	139.49%	69.47%	305.88%
Ireland	81.63%	75.69%	219.11%
Italy	76.26%	18.21%	108.35%
Japan	54.29%	48.15%	128.57%
Netherlands	38.49%	34.87%	86.79%
Portugal	72.43%	7.33%	85.06%
Spain	111.29%	-15.13%	79.31%
Sweden	95.22%	121.68%	332.76%
United Kingdom	146.47%	59.15%	292.25%
United States	48.03%	39.56%	106.58%
Average	76.34%	53.38%	171.23%

4.4 The Relationship between Construction Labor Productivity Improvement and National ICT Investment Improvement

The hypothesis of this chapter is that construction labor productivity positively associates with ICT investment, in other words, the countries with more ICT investment improvement would experience higher construction labor productivity improvement. The author tested this hypothesis with a series of scatter plots and Spearman Rank Correlation.

The author explored the relationship through plotting the sample countries by improvement of construction labor productivity from 1980 to 2003 versus improvement of ICT investment from 1980 to 2000. To differentiate the size of the countries' construction industries, based on the average construction value added from 1980 to 2003, the author marked each country on the scatter plot with different scales. The construction average value added in the 17 countries from 1980 to 2003 was presented in Table 4.3

and the 17 countries were divided into three groups with cut-off points of 10,000 million and 100,000 US dollars (1995 price). Unfortunately, no pattern can be found through this scatter plot (Figure 4.5). The result of Spearman Rank Correlation was consistent with the scatter plot: the Spearman correlation coefficient was -0.150, and the significant level was 0.567, which indicated no significant relationship between the improvement of construction productivity and ICT investment in this period (Table 4.4).

Table 4.3: The Construction Industry Average Value Added, 1980-2003

Group	Country	Average Construction Value Added 1980-2003 (million US dollars, 1995 price)
1	Ireland	3,630
	Portugal	5,502
	Finland	5,844
	Greece	6,064
	Denmark	7,829
2	Sweden	10,054
	Austria	12,885
	Netherlands	18,005
	Australia	20,785
	Canada	30,156
	Spain	35,548
	United Kingdom	49,734
	Italy	53,252
	France	73,269
3	Germany	118,141
	United States	278,210
	Japan	396,856

Note: Japanese average value added is from 1980 to 2002;
The cut-off points are 10,000 and 100,000 million dollars.

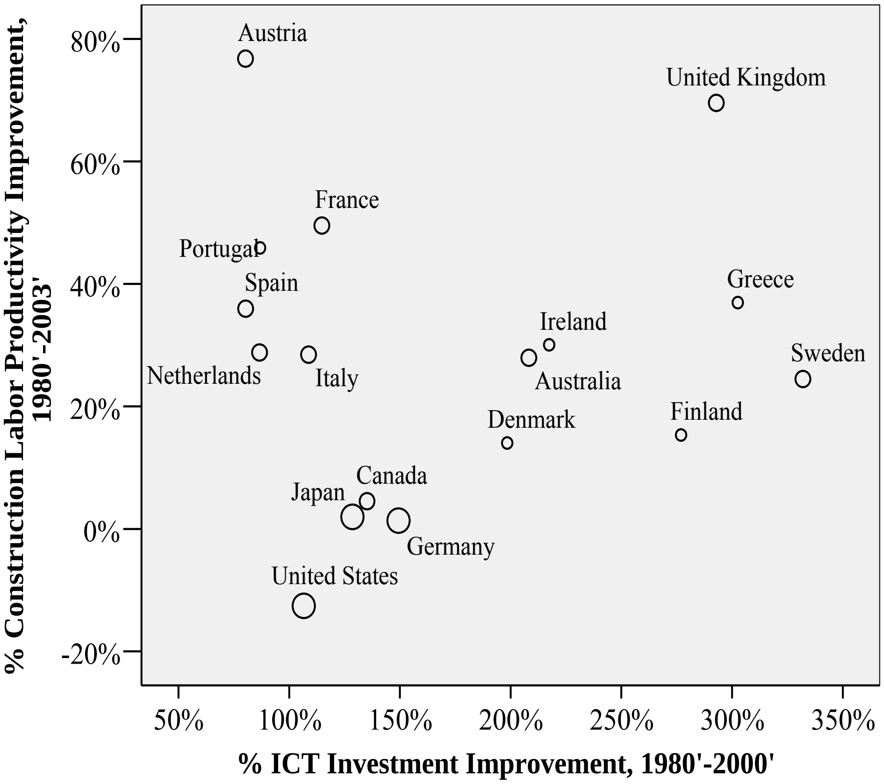

Figure 4.5: Scatter Plot of Construction Labor Productivity Improvement (1980-2003) Vs. National ICT Investment Improvement (1980-2000)

Note: Japanese productivity improvement is from 1990 to 2002;
Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denotes the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

Table 4.4: Spearman Rank Correlation of Construction Labor Productivity Improvement (1980-2003) Vs. National ICT Investment Improvement (1980-2000)

			% ICT Investment Improvement, 1980 to 2000
Spearman's rho	% Productivity Improvement, 1980 to 2003	Correlation Coefficient	-0.150
		Sig. (2-tailed)	0.567
		N	17

Note: Japanese productivity improvement is from 1990 to 2002.

As mentioned in last chapter, since ICT investments can require a long term of around five to fifteen years before the full benefit of the investment is realized, the author next plotted productivity improvement from 1990 rather than 1980 to 2003 and ICT investment from 1980 to 2000 (Figure 4.6).

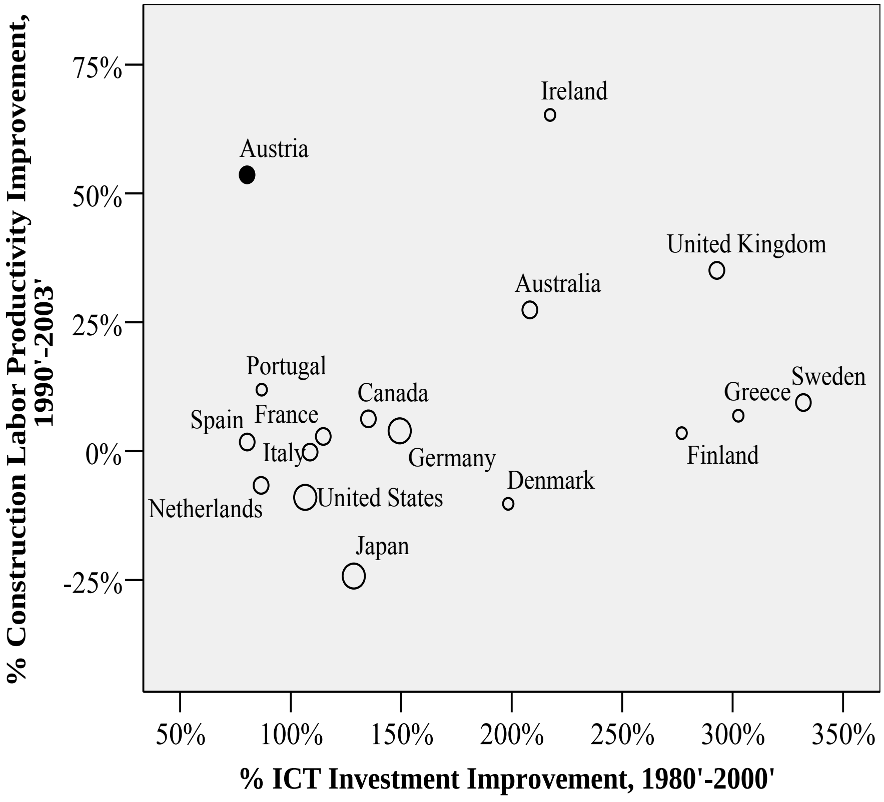

Figure 4.6: Scatter Plot of Productivity Improvement (1990-2003) Vs. National ICT Investment Improvement (1980-2000)

Note: Japanese productivity improvement is from 1990 to 2002;
Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denotes the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

In Figure 4.6, a simple positive relationship can be observed: generally, the countries with higher ICT investment improvement in the period of 1980 to 2000 experienced relatively higher construction labor productivity in the period of 1990 to 2003. Austria seemed to be the exceptions of this pattern because it ranked No.2 by construction productivity improvement with a rank of last No.2 by national ICT investment, respectively. The Spearman Rank Correlation indicated that the correlation coefficient was 0.306 with a significant value of 0.232 (Table 4.5).

Table 4.5: Spearman Rank Correlation of Construction Labor Productivity Improvement (1990-2003) Vs. National ICT Investment Improvement (1980-2000)

			% ICT Investment Improvement, 1980 to 2000
Spearman's rho	% Productivity Improvement, 1990 to 2003	Correlation Coefficient	0.306
		Sig. (2-tailed)	0.232
		N	17

Note: Japanese productivity improvement is from 1990 to 2002.

To further investigate the long term before the construction industry could benefit from national ICT investment, the author then plotted the ICT investment improvement from 1980 to 1990 versus the construction productivity improvement from 1990 to 2003 (Figure 4.7). Figure 4.7 seems to be similar as Figure 4.6, where a simple positive relationship can be observed between the improvements of construction productivity and ICT investment. Austria still seemed to be the exception in this figure, which experienced relatively lower national ICT investment improvement from 1980 to 1990 (ranking last No.2 of 17 countries) and higher construction productivity improvement (ranking No.2 of 17). Again, Spearman Rank Correlation was performed after the scatter plot: the correlation coefficient was 0.380 with a significant value of 0.133 (Table 4.6). Although this result was not significant at the widely accepted 0.05 level, the correlation coefficient was larger than that in Table 4.4 and 4.5 and the associated p-value was less than that in Tables 4.4 and 4.5, which indicated a gap between construction productivity improvement and national ICT investment existed.

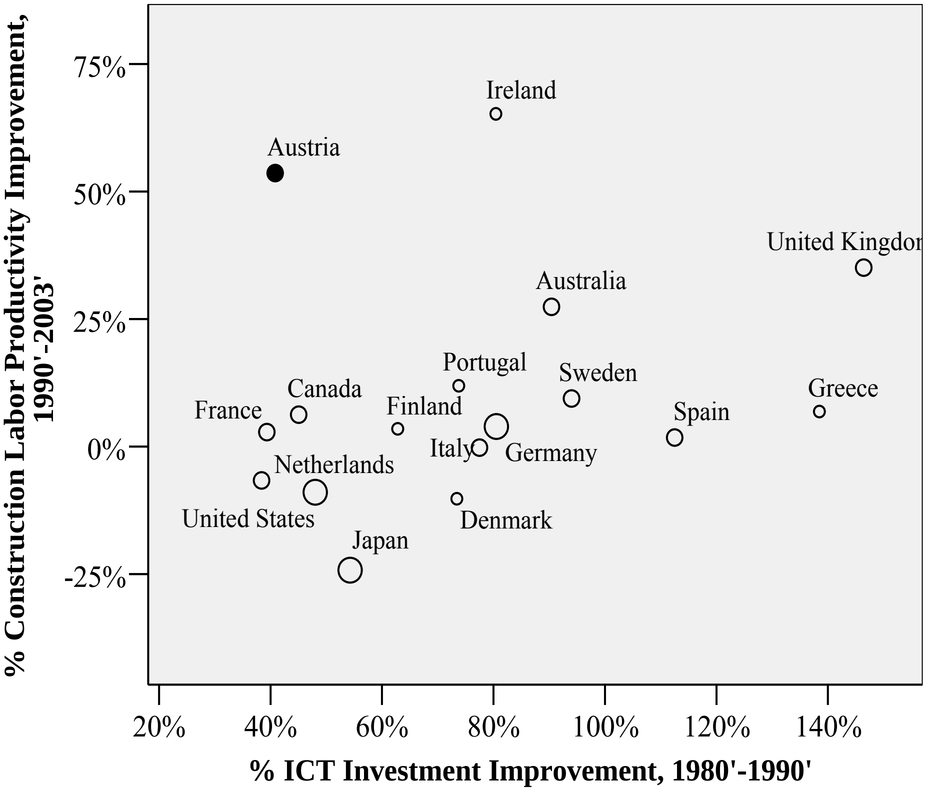

Figure 4.7: Scatter Plot of Construction Labor Productivity Improvement (1990-2003) Vs. National ICT Investment Improvement (1980-1990)

Note: Japanese productivity improvement is from 1990 to 2002;
Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denotes the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

Table 4.6: Spearman Rank Correlation of Construction Labor Productivity Improvement (1990-2003) Vs. National ICT Investment Improvement (1980-1990)

			% ICT Investment Improvement, 1980 to 1990
Spearman's rho	% Productivity Improvement, 1990 to 2003	Correlation Coefficient	0.380
		Sig. (2-tailed)	0.133
		N	17

Note: Japanese productivity improvement is from 1990 to 2002.

As a comparison of Figure 4.7, Figure 4.8 and 4.9 are scatter plots with improvements of construction productivity and ICT investment in the same periods. A pattern can be observed from neither of them. The corresponding Spearman Rank Correlation also indicated there was no significant association in these periods (Table 4.7).

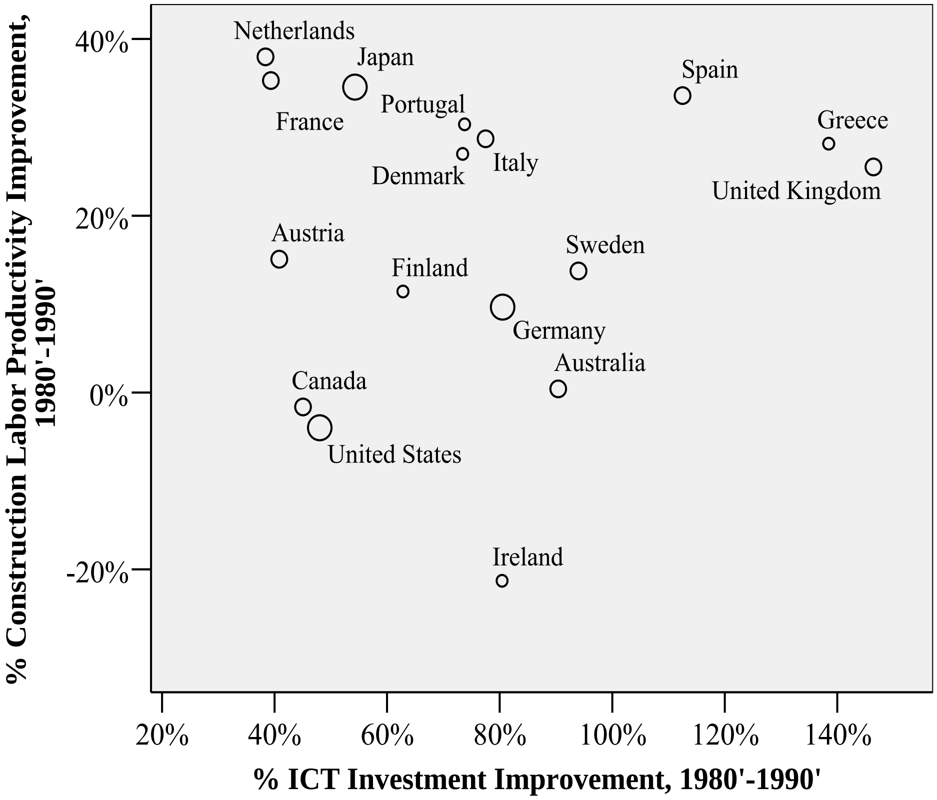

Figure 4.8: Scatter Plot of Construction Labor Productivity Improvement (1980-1990) Vs. National ICT Investment Improvement (1980-1990)

Note: Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denote the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

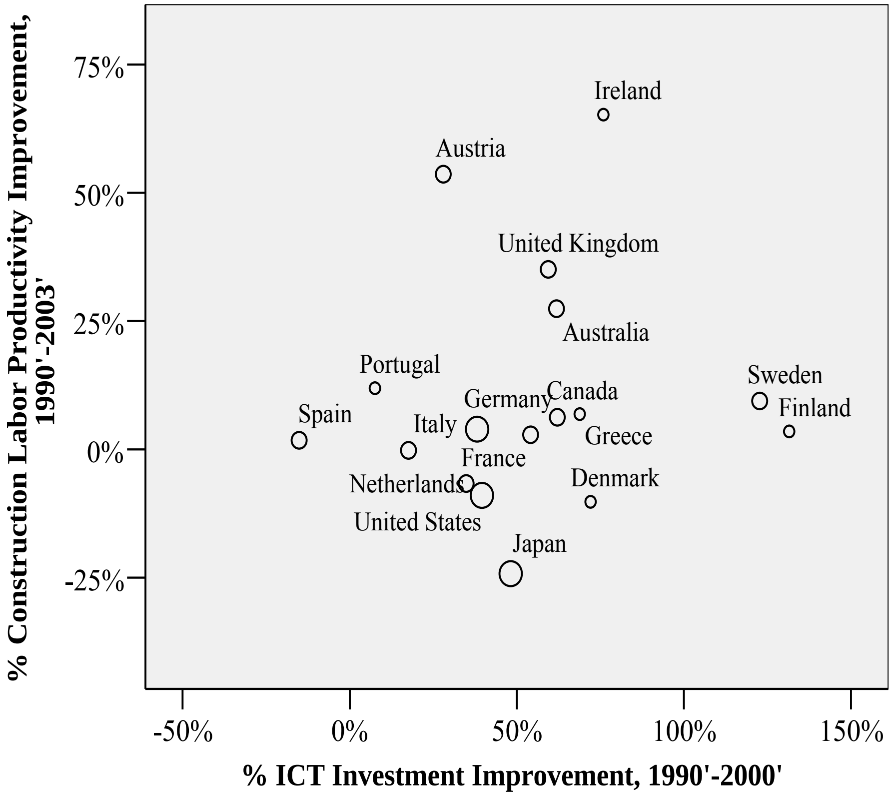

Figure 4.9: Scatter Plot of Construction Labor Productivity Improvement (1990-2003) Vs. National ICT Investment Improvement (1990-2000)

Note: Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denote the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

Table 4.7: Spearman Rank Correlation of Construction Labor Productivity Improvement Vs. National ICT Investment Improvement in Same Periods

				% ICT Investment Improvement	
				1980'-1990'	1990'-2000'
Spearman's rho	% Productivity Improvement	1980'-1990'	Correlation Coefficient	-0.179	N/A
			Sig. (2-tailed)	0.492	
			N	17	
		1990'-2003'	Correlation Coefficient	N/A	0.191
			Sig. (2-tailed)		0.462
			N		17

Notes: Japanese productivity improvement is from 1990 to 2002.

To precisely examine the length of the gap between construction productivity improvement and the national ICT investment, the author performed similar analyses with gaps of one year to 13 years, based on the availability of the data. Finally, the gap of 12 years (Figure 4.10) produced the largest correlation coefficient of 0.409 and the smallest p-value of 0.103 (Table 4.8). Again, with the exception of Austria, the positive relationship was not significant at the 0.05 level, but it was significant at the 0.1 level. The results with a 5-years gap were presented in Figures 4.11 and 4.12 for the purpose of comparison. No patterns can be found from the two scatter plots and the corresponding Spearman Rank Correlation indicated the correlations were much less significant than that with a 12-year gap (Table 4.9). The results with other possible gaps were presented in Appendix C.

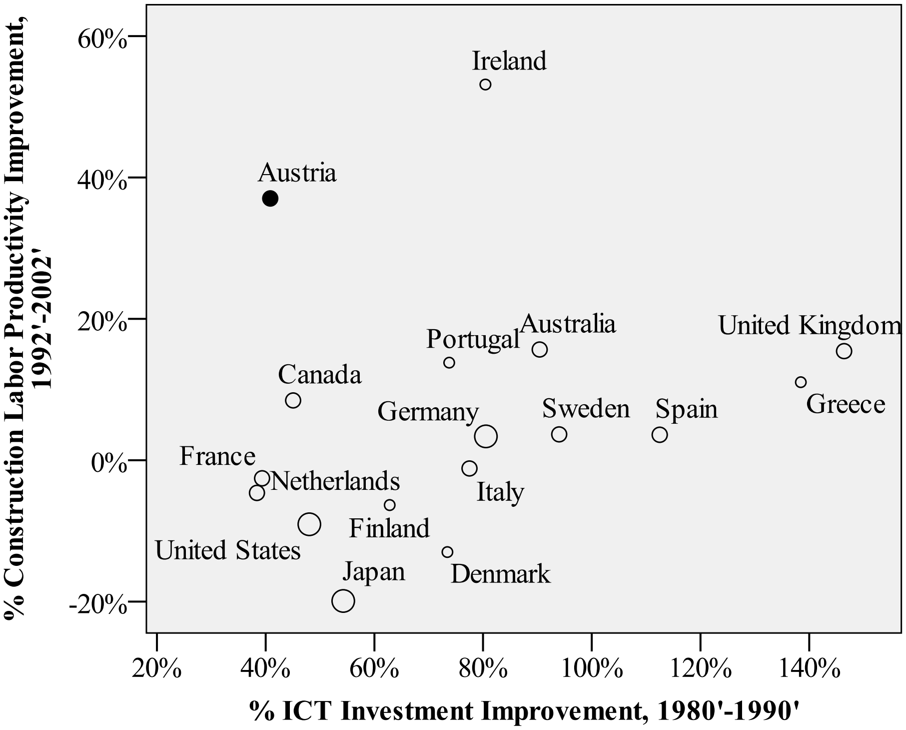

Figure 4.10: Scatter Plot of Construction Labor Productivity Improvement (1992-2002) Vs. National ICT Investment Improvement (1980-1990)

Note: Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denote the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

Table 4.8: Spearman Rank Correlation of Construction Labor Productivity Improvement (1992-2002) Vs. National ICT Investment Improvement (1980-1990)

			% ICT Investment Improvement, 1980 to 1990
Spearman's rho	% Productivity Improvement, 1992 to 2002	Correlation Coefficient	0.409
		Sig. (2-tailed)	0.103
		N	17

Note: Japanese productivity improvement is from 1990 to 2002.

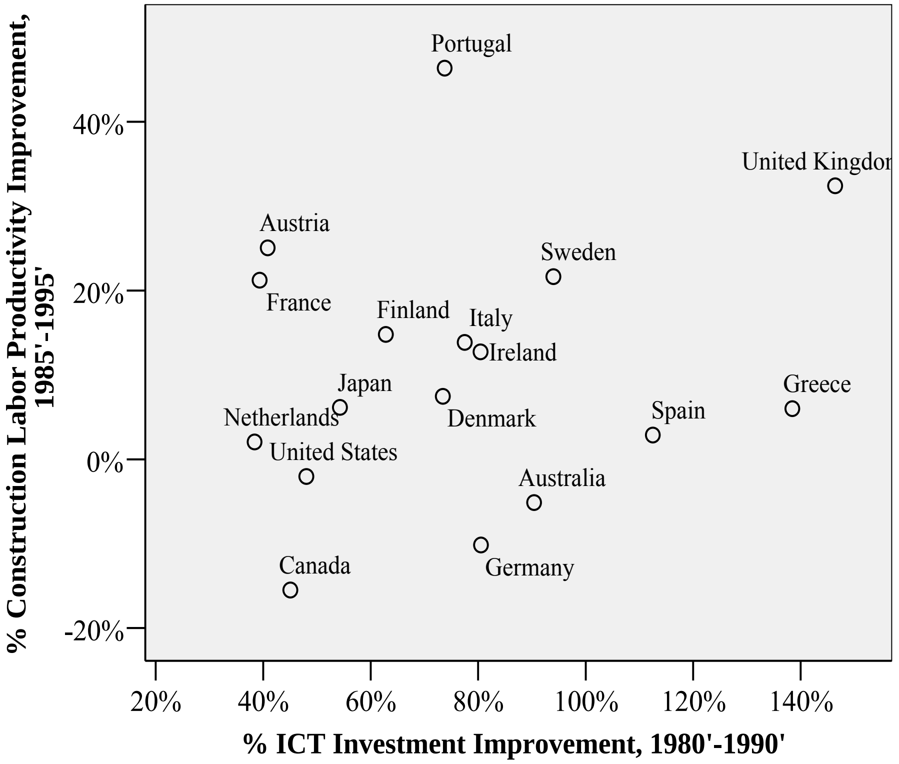

Figure 4.11: Scatter Plot of Construction Labor Productivity Improvement (1985-1995) Vs. National ICT Investment Improvement (1980-1990)

Note: Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denote the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

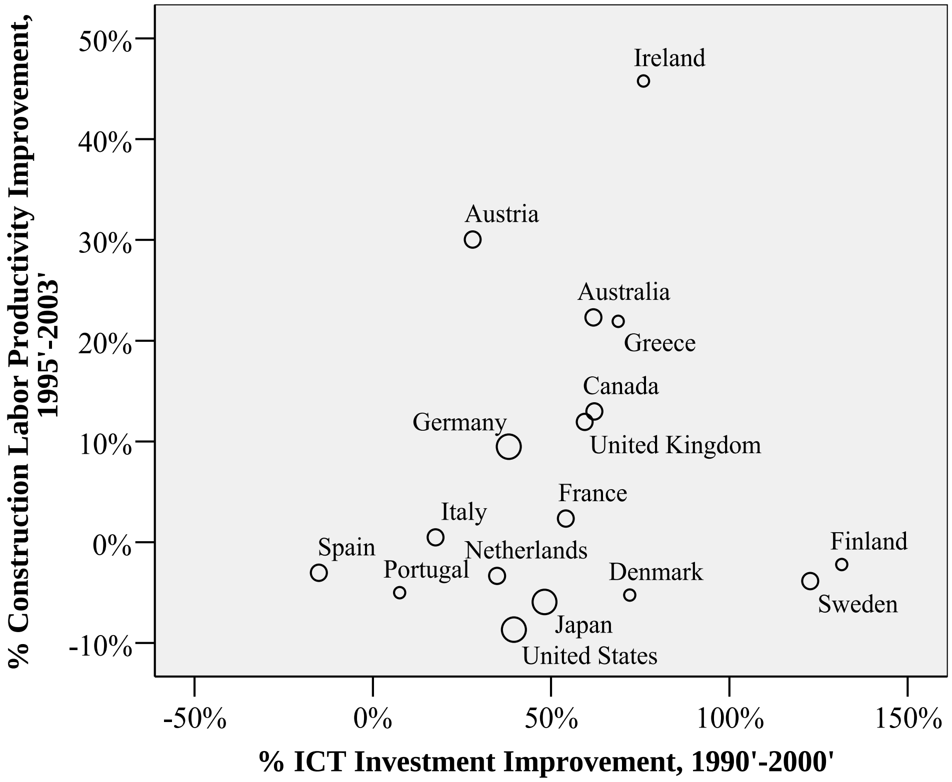

Figure 4.12: Scatter Plot of Construction Labor Productivity Improvement (1995-2003) Vs. National ICT Investment Improvement (1990-2000)

Note: Smallest circles denote the countries' construction value added less than 10,000 1995 US dollars (e.g. Finland); Medium circles denote the countries' average construction value added more than 10,000 but less than 100,000 million 1995 US dollars (e.g. Austria); Largest circles denote the countries' average construction value added more than 100,000 million 1995 US dollars (e.g. United States);
The ICT investment is at national level, not specifically in construction sector.

Table 4.9: Spearman Rank Correlation of Construction Labor Productivity Improvement Vs. National ICT Investment Improvement with 5-year Gaps

				% ICT Investment Improvement	
				1980'-1990'	1990'-2000'
Spearman's rho	% Productivity Improvement	1985'-1995'	Correlation Coefficient	0.296	N/A
			Sig. (2-tailed)	0.283	
			N	17	
		1995'-2003'	Correlation Coefficient	N/A	0.181
			Sig. (2-tailed)		0.486
			N		17

Notes: Japanese productivity improvement is from 1990 to 2002.

Although the focus of this research is on the construction industry, it is natural to raise a question regarding the length of the gap between national ICT investment with other industries' productivity. The author performed similar analysis for the motor vehicles industry as a comparison. The process of motor vehicle manufacturing is known to be more automated than construction. In addition with the development of intensive supply chain processes in the automotive sector, the industry has become heavily reliant on information systems. The author's hypothesis is that the gap between national ICT investment and motor vehicle industry productivity should be shorter than 12 years. The result in Figure 4.13 and Table 4.10 confirmed this guess: with a 6-year gap, a positive relationship can be observed between the motor vehicles industry labor productivity improvement and the national ICT investment. The correlation coefficient is 0.559 and it is significant at the 0.05 level. It is noted that the countries were not marked with different scales based on their motor vehicles industries' average value added in Figure 4.13, because the analysis of this industry is just for the purpose of comparison, but not the focus of this research.

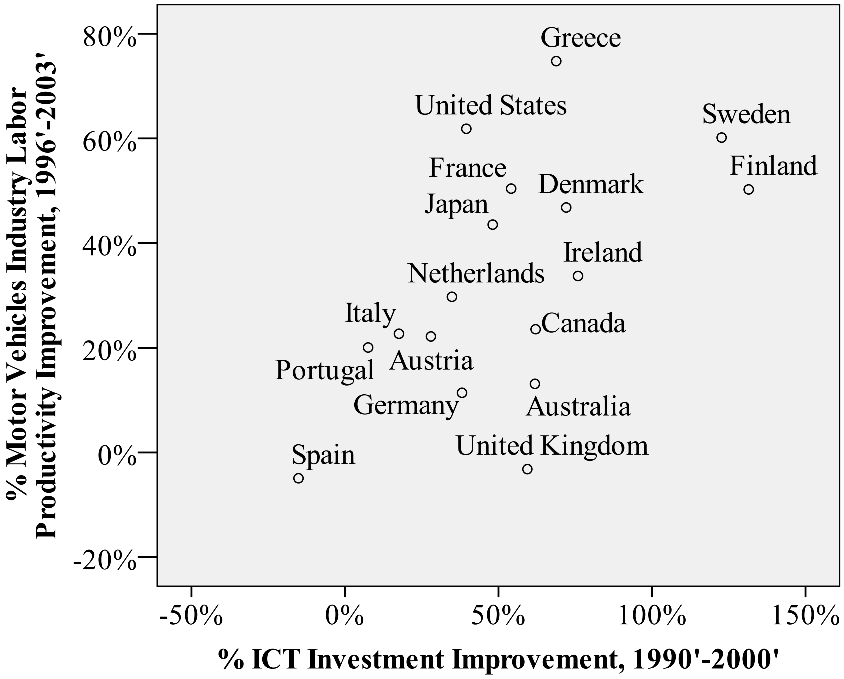

Figure 4.13: Scatter Plot of Motor Vehicles Labor Productivity Improvement (1996-2003) Vs. National ICT Investment Improvement (1990-2000)

Notes: Japanese productivity improvement is from 1990 to 2002

Table 4.10: Spearman Rank Correlation of Motor Vehicles Industry Labor Productivity Improvement (1996-2003) Vs. National ICT Investment Improvement (1990-2000)

			% ICT Investment Improvement, 1990 to 2000
Spearman's rho	% Productivity Improvement, 1996 to 2003	Correlation Coefficient	0.559*
		Sig. (2-tailed)	0.020
		N	17

Note: Japanese productivity improvement is from 1990 to 2002;
* denotes significance at the 0.05 level.

4.5 Summary

The analyses and discussion in this chapter contributed to the body of knowledge with regard to the relationship of construction productivity to information technology development in two areas:

1. A simple positive relationship of construction productivity to national information and communication technology investment can be observed in the national-level although a few countries such as Austria are exceptions.

2. The gap between construction productivity improvement and information technology investment existed, which was about 12 years for the sampled countries in this research.

It should be noted that the long gap is at the industrial and national level, which means it took about 12 years for the whole construction industry in a certain country to benefit its national ICT investment. For a specific company or project, the process may be much shorter.

Future research should investigate more indicators to get a comprehensive assessment of information technology application and development. In addition, the national IT investment level cannot fully represent the IT application in the construction industry. To examine the exact relationship of information technology to construction productivity, more construction-specific data should be collected.

CHAPTER 5 : INDUSTRY LEVEL ANALYSIS

5.1 Introduction of Data Source

The data used in this chapter are also from the Groningen Growth and Development Centre (GGDC), specifically the KLEMS database in the US. The basic building blocks for KLEMS productivity database are the annual industry accounts for the United States provided by U.S Bureau of Economic Analysis (BEA). The KLEMS growth accounts are based on the growth accounting methodology as theoretically motivated by the seminal contribution of Jorgenson and Griliches (1967) and put in a more general input-output framework by Jorgenson, Gollop and Fraumeni (1987) and Jorgenson, Ho and Stiroh (2005). The database includes measures of output growth, employment and skill creation, capital formation and multi-factor productivity at the industry level from 1970 onwards. The input measures include various categories of capital, labor, energy, material and service inputs. The Growth accounting allows one to assess the relative importance of labor, capital and intermediate inputs to growth, and to derive measures of multi-factor productivity (MFP) growth. A key strength of the KLEMS database is that it moves beneath the aggregate economy level to examine the productivity performance of individual industries and their contribution to aggregate growth (Timmer et al, 2007). From this database the author collected the volume indices of labor productivity as the relative gross value added per hour worked (1995=100) and contribution of ICT capital to value added growth as percentage points.

5.2 The Construction Industry

5.2.1 Productivity

Similar as previous studies based on aggregate data (Stokes 1981, BRT 1983, Allen 1985, Teicholz 2000), the author observed that the construction labor productivity decreased by 13.94% from 1980 to 2005 and the annual compound decreasing rate of 0.60% in this research (Figure 5.1). Although the general trend was decreasing, there were still some short periods when construction labor productivity increased. The longest period with increasing construction productivity was from 1982 to 1986 with an annual compound 3.19%. The highest productivity appeared on 1980 and the lowest one on 2004, which confirmed the long-term decreasing trend. However, it should be noted again that any construction productivity related research based on the aggregate measurement or macro industrial level is inevitably subject to the problem of inaccurate real output.

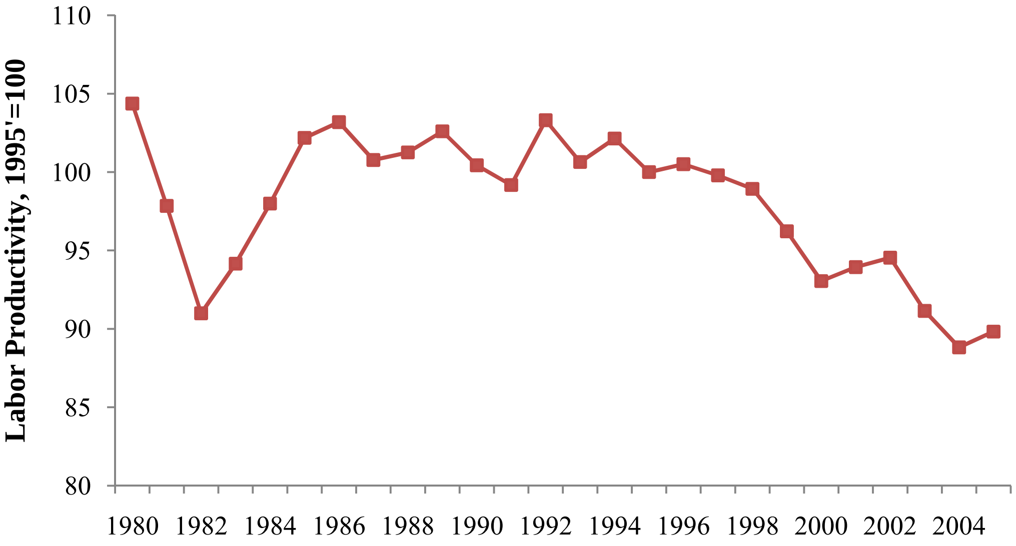

Figure 5.1: Construction Productivity Trends (1980-2005)

Data Source: GGDC KLEMS database

5.2.2 ICT Contribution

It can be observed that the contribution of ICT capital input growth to value added growth in the construction industry experienced a long-term increase from 1980 to 2005 (Figure 5.1). The ICT contribution in 2005 was 44.6 times of that in 1980 and the annual increasing rate was 16.51%. Although the construction industry has traditionally been viewed as technologically stagnant in comparison with other industries (Rosefielde and Mills 1979), the impact of information technology was still tremendous in the long run. Specifically, the ICT contribution continued to increase before 1998 and reached its peak in 1998. After 1998, ICT contribution experienced an obvious decrease and had a fluctuant trend in the new century.

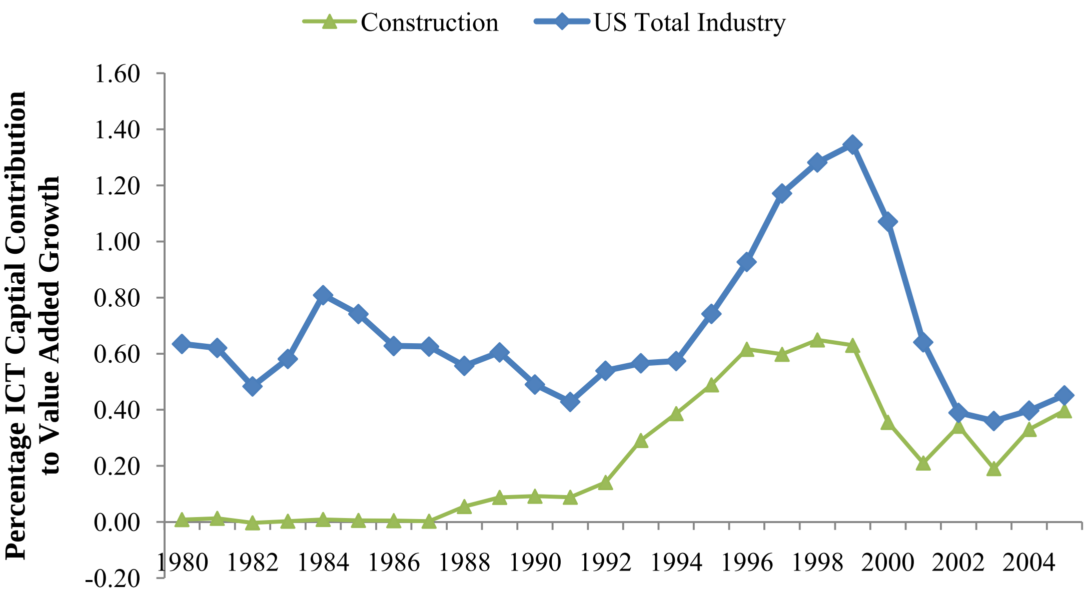

Figure 5.2: Contribution of ICT Capital to Construction and US Total Value Added Growth (1980-2005)

Data Source: GGDC KLEMS database

5.2.3 Growth Accounting Analysis

A decomposition of value added growth in the construction industry from 1980 to 2005 was given in Table 5.1 and Figure 5.2. All basis data in Table 5.1 is from GGDC KLEMS database, while the author calculated the average for different periods. It can be observed that construction value added growth was primarily impacted by the contribution of labor input growth and multi factor productivity growth. Generally, the former had a positive contribution and the latter had a negative contribution. It can also be observed that from 1980 to 1990, the contribution of ICT capital was very minor; while after 1990, the contribution of ICT capital began to play a more important role in the construction value added growth. In addition, unlike the contribution of Non-ICT capital, the contribution of ICT capital to construction value added growth was always positive. Except in the period of 1996 to 2000, the contribution of ICT capital to value added growth was more than the contribution from the Non-ICT capital in the construction industry.

Table 5.1: Gross Value Added Growth and Contributions in Construction Industry, 1980-2005 (Annual average volume growth rate, in %)

	VA	L	K	KIT	KNIT	MFP
	(1)= (2)+(3)+(6)	(2)	(3)= (4)+(5)	(4)	(5)	(6)
1980-1985	-0.43	1.02	-0.15	0.01	-0.15	-1.30
1986-1990	1.81	2.25	0.00	0.05	-0.05	-0.44
1991-1995	-0.08	0.31	0.40	0.28	0.12	-0.79
1996-2000	2.93	4.03	1.35	0.57	0.78	-2.45
2001-2005	0.27	0.98	0.54	0.29	0.24	-1.25

Note: VA= Gross Value Added Growth
L= Contribution of Labor Input Growth
K= Contribution of Capital Input Growth
KIT= Contribution of ICT Capital
KNIT= Contribution of Non-ICT Capital
MFP= Contribution of Multi Factor Productivity Growth
Data is from GGDC KLEMS database.

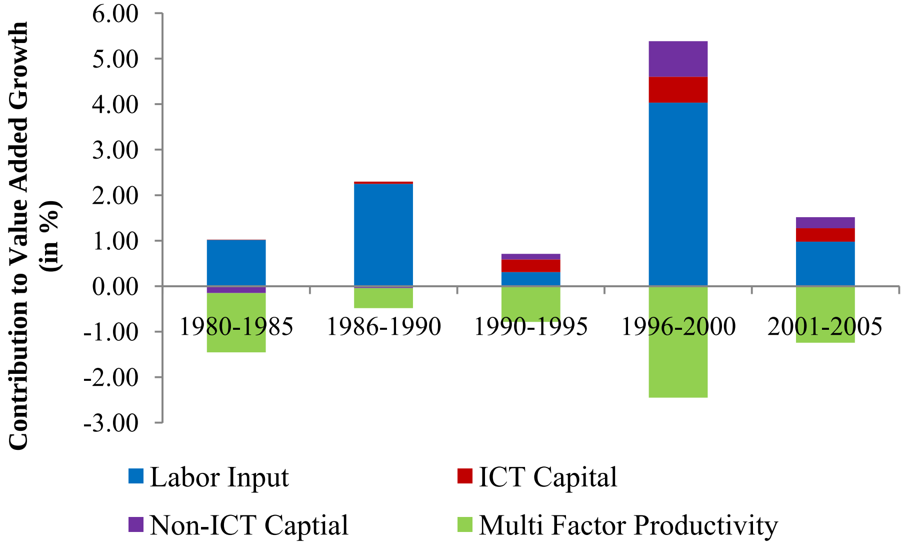

Figure 5.3: Contribution to Construction Value Added Growth 1980-2005 (in %)

Data Source: GGDC KLEMS database

5.3 The Total US Industries

5.3.1 Productivity

Unlike the construction industry, the total US industries experienced a long term productivity increase from 1980 to 2005 (Figure 5.4). In this period, the productivity increased by 52.00% with an annual compound rate of 1.69%. It can also be observed from Figure 5.4 that the increase was a long-term and steady process, which means the annual increasing rate was generally similar in any period of these years.

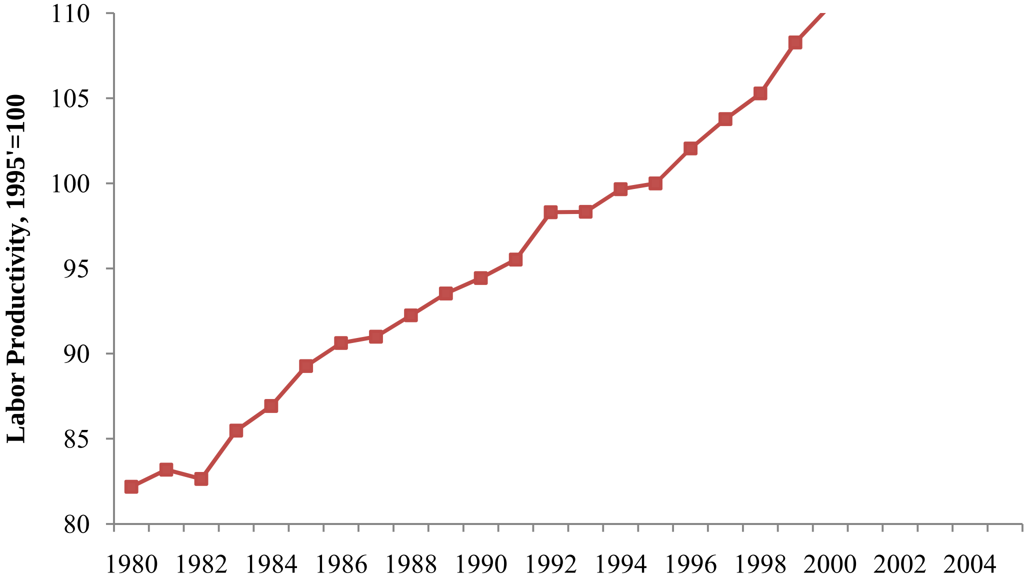

Figure 5.4: The Total US Industry Productivity Trends (1980-2005)

Data Source: GGDC KLEMS database

Table 5.2 showed all of the US industries' labor productivity improvement at the aggregate level from 1980 to 2005. The electrical and optical equipment industry experienced the largest labor productivity improvement of 2271.68%, followed by the textiles, textile, leather and footwear industry with an improvement of 170.75% and the total manufacturing with an improvement of 169.98%. Health and social work, construction and education are the three industries with largest decrease on labor productivity, and the decreases are 24.05%, 13.94% and 8.74%, respectively.

Table 5.2: All US Industries' Labor Productivity Improvement, 1980-2005

Industry	Productivity Improvement (1980-2005)
TOTAL INDUSTRIES	52.00%
AGRICULTURE, HUNTING, FORESTRY AND FISHING	142.74%
MINING AND QUARRYING	68.20%
TOTAL MANUFACTURING	169.98%
FOOD , BEVERAGES AND TOBACCO	31.21%
TEXTILES, TEXTILE , LEATHER AND FOOTWEAR	170.75%
WOOD AND OF WOOD AND CORK	32.55%
PULP, PAPER, PAPER , PRINTING AND PUBLISHING	24.02%
CHEMICAL, RUBBER, PLASTICS AND FUEL	162.89%
OTHER NON-METALLIC MINERAL	70.73%
BASIC METALS AND FABRICATED METAL	76.21%
MACHINERY, NEC	57.52%
ELECTRICAL AND OPTICAL EQUIPMENT	2271.68%
TRANSPORT EQUIPMENT	88.90%
MANUFACTURING NEC; RECYCLING	114.29%
ELECTRICITY, GAS AND WATER SUPPLY	166.20%
CONSTRUCTION	-13.94%
WHOLESALE AND RETAIL TRADE	138.20%
HOTELS AND RESTAURANTS	15.27%
TRANSPORT AND STORAGE AND COMMUNICATION	93.95%
TRANSPORT AND STORAGE	78.22%
POST AND TELECOMMUNICATIONS	146.00%
FINANCE, INSURANCE, REAL ESTATE AND BUSINESS SERVICES	11.61%
FINANCIAL INTERMEDIATION	47.62%
REAL ESTATE, RENTING AND BUSINESS ACTIVITIES	-1.39%
COMMUNITY SOCIAL AND PERSONAL SERVICES	-0.76%
PUBLIC ADMIN AND DEFENCE; COMPULSORY SOCIAL SECURITY	16.85%
EDUCATION	-8.74%
HEALTH AND SOCIAL WORK	-24.05%
OTHER COMMUNITY, SOCIAL AND PERSONAL SERVICES	49.39%

Data Source: GGDC KLEMS database

5.3.2 ICT Contribution

Similar as the construction industry, the contribution of ICT capital input growth to value added growth in the total US industries also had a fluctuant trend from 1980 to

2005 (Figure 5.2). The lowest ICT contribution was in 2003, and the highest ICT contribution was in 1999. The longest period with increasing ICT contribution was from 1991 to 1999 with an annual increasing rate of 15%. Compared with the construction industry, the contribution of ICT capital to total US industry's value added growth is generally higher, but the difference between them has decreased in the long term. Although in the period from 1997 to 2000, the difference increased, after 2001 it decreased significantly.

Due to the fluctuant trend of ICT contribution, it is better to investigate it in a relative short period as the author have mentioned in Chapter 3. Table 5.3 showed the ICT capital contribution to value added growth for all US industries in the five periods from 1980 to 2005. The position of the construction industry regarding the ICT capital contribution can be observed from this table. Generally speaking, construction is an industry with relative low ICT capital contribution to value added growth in any period. Specifically, from 1980 to 1985, it has the lowest ICT contrition and in the next four periods it ranks last 3rd, last 5th, last 11th and last 13th in the 29 industries regarding the ICT contribution to value added growth, respectively. However, a positive trend is that the rank increased anyway, which is an indication that the construction industry has gradually increased the application of information and communication technology and benefited from that.

Table 5.3: ICT Contribution to Value Added Growth in All US Industries, 1980-2005

Industry	**Average Annual ICT contribution to Value Added Growth (in %)**				
	1980-1985	**1985-1990**	**1990-1995**	**1995-2000**	**2000-2005**
TOTAL INDUSTRIES	0.65	0.61	0.56	1.09	0.55
AGRICULTURE, HUNTING, FORESTRY AND FISHING	0.02	0.05	0.13	0.15	0.10
MINING AND QUARRYING	0.43	0.02	0.38	0.63	0.24
TOTAL MANUFACTURING	0.52	0.52	0.56	0.89	0.30
FOOD , BEVERAGES AND TOBACCO	0.37	0.42	0.40	0.59	0.31
TEXTILES, TEXTILE , LEATHER AND FOOTWEAR	0.14	0.12	0.22	0.28	0.06
WOOD AND OF WOOD AND CORK	0.29	0.21	0.27	0.31	0.13
PULP, PAPER, PAPER , PRINTING AND PUBLISHING	0.59	0.78	0.44	0.69	0.31
CHEMICAL, RUBBER, PLASTICS AND FUEL	0.46	0.61	0.79	1.07	0.43
OTHER NON-METALLIC MINERAL	0.56	0.48	0.21	0.58	0.28
BASIC METALS AND FABRICATED METAL	0.36	0.30	0.36	0.44	0.16
MACHINERY, NEC	0.65	0.48	0.72	1.58	0.47
ELECTRICAL AND OPTICAL EQUIPMENT	0.81	0.58	0.90	1.36	0.18
TRANSPORT EQUIPMENT	0.63	0.58	0.39	0.92	0.23
MANUFACTURING NEC; RECYCLING	0.39	0.49	0.47	0.59	0.32
ELECTRICITY, GAS AND WATER SUPPLY	0.84	0.58	0.38	0.61	0.53
CONSTRUCTION	**0.01**	**0.04**	**0.25**	**0.56**	**0.30**

Table 5.3: ICT Contribution to Value Added Growth in All US Industries, 1980-2005 (Continue)

Industry	**Average Annual ICT contribution to Value Added Growth (in %)**				
	1980-1985	**1986-1990**	**1991-1995**	**1996-2000**	**2001-2005**
WHOLESALE AND RETAIL TRADE	0.78	0.48	0.53	0.88	0.56
HOTELS AND RESTAURANTS	0.20	0.12	0.12	0.19	0.19
TRANSPORT AND STORAGE AND COMMUNICATION	0.65	0.65	1.13	2.94	1.19
TRANSPORT AND STORAGE	0.29	0.25	0.72	1.80	0.83
POST AND TELECOMMUNICATIONS	0.99	1.01	1.47	3.97	1.52
FINANCE, INSURANCE, REAL ESTATE ANBUSINESS SERVICES	1.26	1.19	0.76	1.67	0.83
FINANCIAL INTERMEDIATION	2.82	2.47	1.73	2.68	1.18
REAL ESTATE, RENTING AND BUSINESS ACTIVITIES	0.74	0.77	0.43	1.30	0.70
COMMUNITY SOCIAL AND PERSONAL SERVICES	0.27	0.35	0.35	0.44	0.30
PUBLIC ADMIN AND DEFENCE; COMPULSORY SOCIAL SECURITY	0.30	0.42	0.38	0.52	0.32
EDUCATION	0.25	0.36	0.39	0.59	0.36
HEALTH AND SOCIAL WORK	0.23	0.30	0.29	0.33	0.31
OTHER COMMUNITY, SOCIAL AND PERSONAL SERVICES	0.26	0.25	0.33	0.28	0.19

Data Source: GGDC KLEMS database

5.3.3 Growth Accounting Analysis

Similarly, a decomposition of value added growth for the total US industries from 1980 to 2005 is given in Table 5.4 and Figure 5.5. Generally, the capital input growth was the most important factors that impacted the value added growth. Except the period between 1996 and 2000, the contribution of Non-ICT capital was more than that of ICT capital, but the difference between the contribution of Non-ICT capital and ICT capital has decreased in the long term, which means the importance of ICT capital increased in the capital formation regarding the impacts on the value added growth.

Table 5.4: Gross Value Added Growth and Contributions, 1980-2005
(Annual average volume growth rate, in %)

	VA	L	K	KIT	KNIT	MFP
	(1)= (2)+(3)+(6)	(2)	(3)= (4)+(5)	(4)	(5)	(6)
1980-1985	2.37	0.91	1.64	0.65	1.00	-0.18
1986-1990	3.05	1.40	1.47	0.58	0.89	0.17
1991-1995	2.15	0.81	1.29	0.57	0.72	0.04
1996-2000	4.04	1.53	2.14	1.16	0.98	0.36
2001-2005	2.34	0.11	1.04	0.45	0.59	1.19

Note: VA= Gross Value Added Growth
L= Contribution of Labor Input Growth
K= Contribution of Capital Input Growth
KIT= Contribution of ICT Capital
KNIT= Contribution of Non-ICT Capital
MFP= Contribution of Multi Factor Productivity Growth
Data is from GGDC KLEMS database.

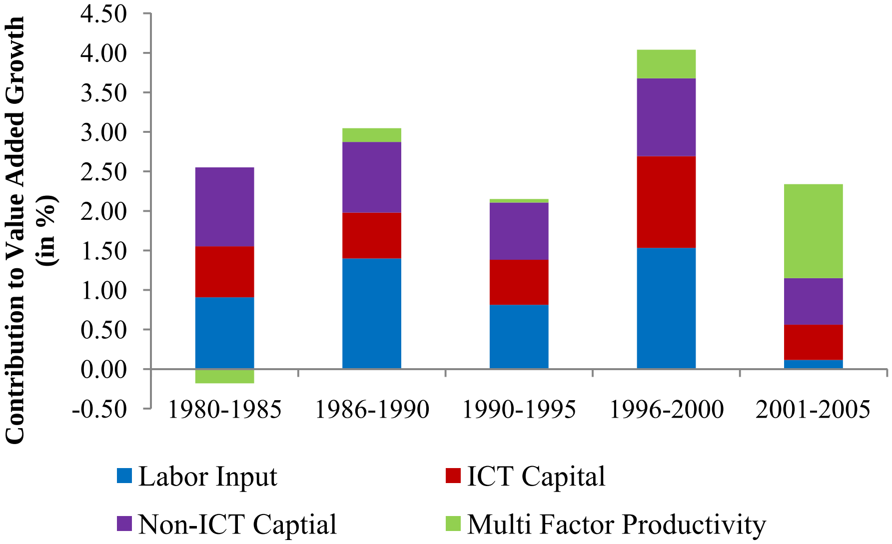

Figure 5.5: Contribution to Total US Industries Value Added Growth 1980-2005 (in %)

Data Source: GGDC KLEMS database

5.4 The Relationship between ICT Capital Contribution and Productivity Improvement

The hypothesis of this section is that the US industries' labor productivity positively associates with the ICT capital contribution to value added growth, in other words, the industries with higher ICT capital contribution to their value added growth would experience higher labor productivity improvement. The author tested this hypothesis with a series of *t*-tests. For purposes of the analysis, industries with ICT capital contribution above the overall median among all sampled industries were classified as having a high ICT contribution, and projects with ICT contribution below the median were defined as having a low ICT contribution. The author tested if there were statistically significant difference between the two groups.

5.4.1 The Relationship of Labor Productivity and ICT Contribution in Same Periods

First, the author tested the relationship of labor productivity improvement and ICT capital contribution to value added growth with both of them in the same periods, i.e. labor productivity improvement versus average ICT capital contribution to value added growth in the periods of 1980-1985, 1985-1990, 1990-1995, 1995-2000 and 2000-2005. Table 5.5 showed the results of *t*-tests, which indicated there was no statistically positive difference on the labor productivity improvement between the industries with high ICT contribution and those with relative low ICT contribution, except in the period from 1995 to 2000. In addition, there were two periods (1980-1985 and 2000-2005) when the industries with low ICT contribution has greater labor productivity improvement than those with high ICT contribution, although the difference was statistically significant only in the period of 2000-2005. One possible reason is the ICT capital needs a long period to realize its potential to improve productivity and an industry also needs a period to adapt itself to new technologies.

5.4.2 The Relationship of Labor Productivity and ICT Contribution with a 10-year Gap

The previous chapter indicated that there was a gap of about 12 years between the construction labor productivity improvement and ICT investment in the sampled countries including the U.S. Therefore, the author tested if a similar gap also existed in this industry-level analysis in the U.S. Specifically, the author repeated the *t*-tests showed in Table 5.5, but investigated the relationship with a 10-year gap between ICT capital contribution and labor productivity improvement rather than in same periods. For example, the author grouped the sampled industries based on their average ICT capital contribution to value added growth from 1980 to 1985, and tested if the difference of productivity improvement from 1990 to 1995 between the two groups was significant. The results were shown in Table 5.6, which indicated in all of the three periods, the industries with higher ICT contribution experienced greater labor productivity improvement than those with lower ICT contribution, and the difference were statistically significant at the 0.05 level. The gap between ICT capital contribution and labor productivity improvement was about 10 years.

Table 5.5: Result of *t*-test (Labor Productivity Improvement vs. ICT Contribution in same periods)

Period	Labor Productivity Improvement (%)			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
	High ICT Contribution Industry	Low ICT Contribution Industry	Difference	F	Sig.	t	Sig.	t	Sig.
1980-1985	10.93(19)	24.69(19)	-13.76	1.32	0.26	-12.28	0.21	-1.28	0.21
1985-1990	10.72(17)	6.22(18)	4.50	1.92	0.18	0.84	0.41	0.82	0.42
1990-1995	15.61(19)	7.52(19)	8.09	0.22	0.65	1.36	0.18	1.36	0.19
1995-2000*	24.91(19)	6.46(19)	18.45	3.30	0.08	2.22	0.03	2.22	0.03
2000-2005*	12.87(18)	25.10(17)	-12.23	0.35	0.56	-2.14	0.04	-2.11	0.04

Note: * denotes significance at 0.05, and the numbers in the parentheses are the numbers of industries.

Table 5.6: Result of *t*-test (Labor Productivity Improvement vs. ICT Contribution with 10-year Gap)

Period	Labor Productivity Improvement (%)			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
	High ICT Contribution Industry	Low ICT Contribution Industry	Difference	F	Sig.	t	Sig.	t	Sig.
LP (1990-1995) vs. ICT (1980-1985)*	62.27(18)	18.45(18)	43.82	1.42	0.24	2.12	0.04	2.12	0.04
LP (1995-2000) vs. ICT (1985-1980)*	25.09(17)	6.76(18)	18.32	2.83	0.10	2.03	0.05	1.98	0.06
LP (2000-2005) vs. ICT (1990-1995) **	25.95(19)	11.47(19)	14.48	0.08	0.78	2.83	0.01	2.83	0.01

Note: LP denotes labor productivity;
* denotes significance at 0.05, and ** denotes significance at 0.01;
The numbers in the parentheses are the numbers of industries.

5.5 Summary

This chapter investigated the relationship between labor productivity improvement and information technology from the aspect of ICT capital contribution to an industry's value added growth. The major findings are as follows:

1. In the U.S construction industry, the contribution of ICT capital to value added growth increased in the long term, and generally the contribution of ICT capital was greater than the Non-ICT capital.

2. From 1980 to 2005, the construction industry's ranking was low in the total U.S industries, by labor productivity improvement and ICT capital contribution to value added growth. But the ranking of ICT contribution to construction productivity has increased in the long term.

3. A statistically positive relationship can be observed between ICT capital contribution and labor productivity improvement in the U.S total industries, i.e. the industries with higher ICT contribution experienced greater labor productivity improvement than those with lower ICT contribution. A gap about 10 years was observed between the ICT contribution and labor productivity improvement. It is noted that the author didn't test every possible gap like last chapter, because the focus of this research is construction industry rather than the total industry.

CHAPTER 6 : PROJECT LEVEL ANALYSIS

6.1 Introduction of the Benchmarking and Metrics Productivity Database

The data used in this chapter are from the Construction Industry Institute's (CII's) Benchmarking and Metrics (BM&M) Productivity Database 9.0. The BM&M program aims to measure and assess capital project performance and find the best practice among similar projects. The dataset is intended to allow participating companies to compare their own projects with similar ones, and improve their performance through implementing the recommended practices identified by the program. The database includes 86 projects, providing information about project description, field practices and unit rate productivity. Breakdown of project's industrial group and type are presented in Tables 6.1 and 6.2. The majority of the projects are heavy industrial construction such as chemical manufacturing, electrical (generating) and oil refining projects.

Table 6.1: Project Industrial Group Breakdown

Industry Group	Frequency	Percent
Heavy Industrial	74	86.0
Light Industrial	7	8.1
Infrastructure	4	4.7
Buildings	1	1.2
Total	86	100.0

Table 6.2: Project Type Breakdown

Project Type	Frequency	Percent	Cumulative Percent
Chemical Mfg.	35	40.7	40.7
Electrical (Generating)	11	12.8	53.5
Oil Refining	10	11.6	65.1
Pulp and Paper	7	8.1	73.3
Natural Gas Processing	4	4.7	77.9
Heavy Industrial	3	3.5	81.4
Oil Exploration/Production	3	3.5	84.9
Pharmaceutical Bulk Manufacturing	3	3.5	88.4
Consumer Products Mfg.	2	2.3	90.7
Foods	2	2.3	93.0
Environmental	1	1.2	94.2
Flood Control	1	1.2	95.3
Highway	1	1.2	96.5
Laboratory	1	1.2	97.7
Marine Facilities	1	1.2	98.8
Water/Wastewater	1	1.2	100.0
Total	86	100.0	

The field practices include different aspects of jobsite management systems such as materials management, constructability, and automation and integration of project systems among others. In this research, only the field practices of automation and integration of construction systems among the sampled projects along with their corresponding unit rate productivity were examined. The database collected activity productivity data among a variety of construction tasks from seven trades. The CII unit rate productivity metrics, including the definition of the measuring activities and tasks, were identified through the use of literature reviews, documentation from owner and contractor organizations, and a series of workshops with industry experts (Park et al 2005). Details on its methods of data collection and standard accounts have been well documented elsewhere (Park et al 2005). As mentioned in Chapter 3, for the purpose of this research, only task unit rate productivities in four common trades were examined: concrete, structural steel, electrical and piping, due to restrictions in sample sizes.

The data in CII's BM&M database were collected through two different questionnaires, one for large projects and the other for small projects. The projects with installed costs less than 5 million dollars were defined as small projects and those with more than 5 million dollars installed costs were defined as large projects. The analyses in this chapter were also separated to large projects and small projects.

6.2 Analyses of Large Projects

6.2.1 Descriptive Statistics of Large Projects

In total, 339 activities from 30 projects were included in the large projects' analyses. Although 39 of the 86 projects can be identified as large projects, only in 30 of the 39 projects were both the unit rate productivity measurement in the four trades and the automation and integration use levels available. Missing data in the other 9 projects prevented their inclusion in the analyses. The descriptive statistics for the activities' normalized unit rate productivity are presented in Table 6.3. The means of the normalized unit rate productivities from the four trades ranged from 3.50 for concrete to 4.18 for the piping trade.

Table 6.3: Descriptive Statistics of Large Projects' Normalized Unit Rate Productivity

Trade	N（Activities）	Mean	Min	Max	Sta.Dev	95% Confidence Interval of the Mean	
						Lower	upper
Concrete	81	3.50	1	10	2.33	2.99	4.02
Structural Steel	75	4.15	1	10	2.46	3.58	4.72
Electrical	85	3.88	1	10	2.85	3.27	4.50
Piping	98	4.18	1	10	2.98	3.58	4.78

Next, the average automation use level for each work function among the 30 sampled projects was calculated. As shown in Figure 6.1, the average automation use levels on all of the work functions are greater than 3.00, except business planning. The average automation index is 5.72 (on a 0 to 10 scale) with a 95% confidence interval from 5.53 to

5.90, and its distribution among the sampled projects was shown in Figure 6.2. The work function with highest automation use level is cost system, followed by schedule system.

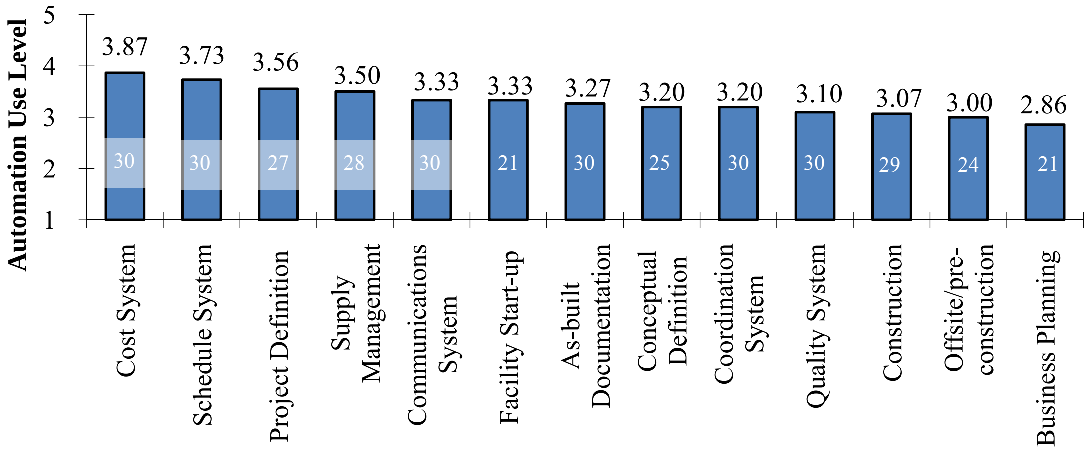

Figure 6.1: The Average Automation Use Level on Each Work Function (Large Projects)

Note: The numbers on the bars are the sample sizes (number of projects)

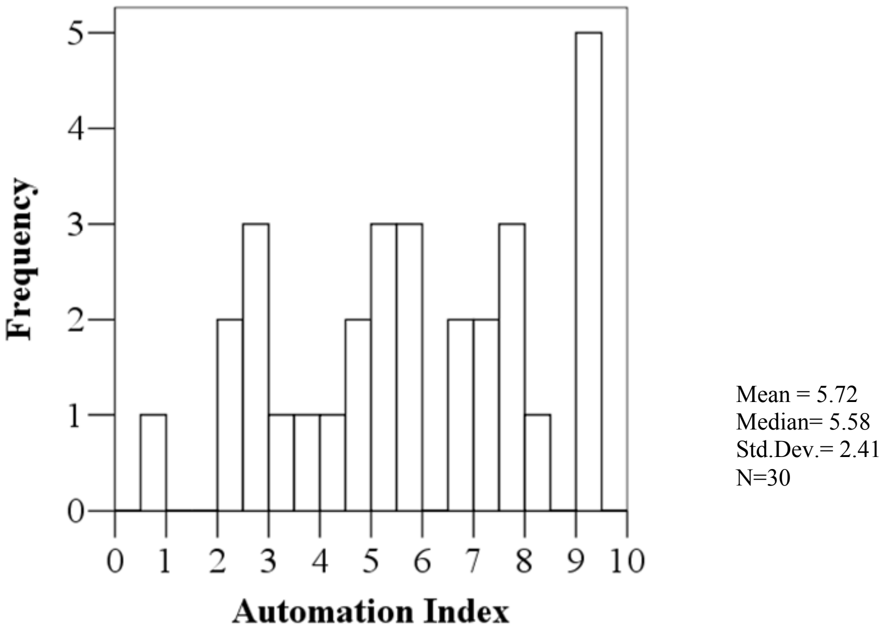

Figure 6.2: The Histogram of Automation Index Distribution for the Sampled Large Projects

The average integration use level on the 13 work functions is greater than 3.00 (Figure 6.3), and the average integration index is 5.98 (on a 0 to 10 scale) with a 95% confidence interval from 5.80 to 6.16 (Figure 6.4). The work function with lowest integration use level is offsite/pre-construction, followed by as-built documentation. The work function with highest integration use level is still cost system, followed by schedule system. Due to the importance of cost and schedule on construction project performance, it is not unexpected that the two work functions are of the highest automation and integration use level.

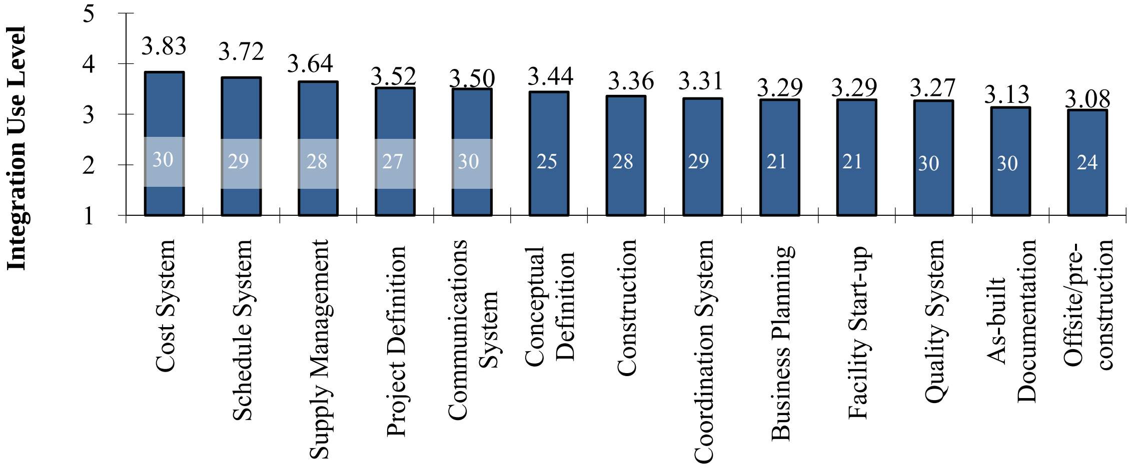

Figure 6.3: The Average Integration Use Level on Each Work Function (Large Projects)

Note: The numbers on the bars are the sample sizes (number of projects)

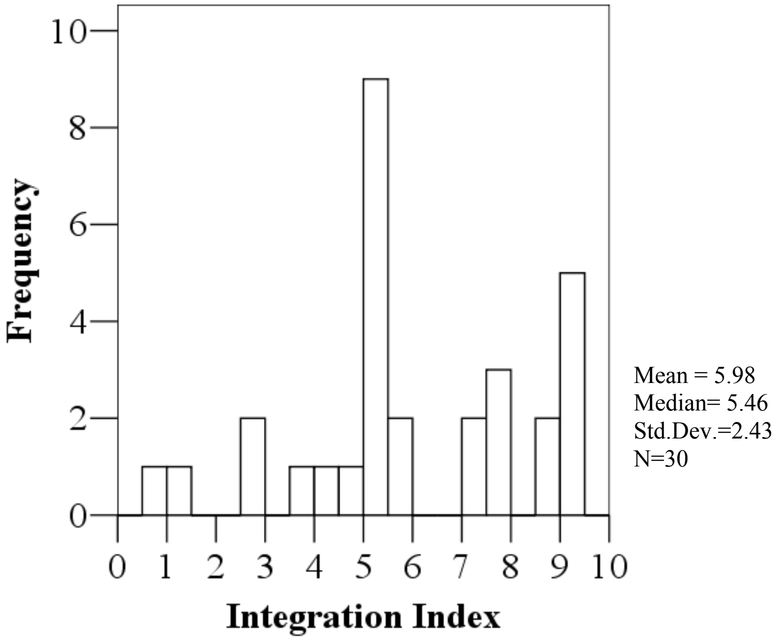

Figure 6.4: The Histogram of Integration Index Distribution for the Sampled Large Projects

6.2.2 Analysis by Work Functions with Actual Productivity Comparison

The results of the *t*-tests that examined differences in activity unit rate productivity considering the level of automation and integration achieved in the respective project work functions were presented herein. Only the work functions which experienced a statistically significant relationship with unit rate productivity and automation and integration of its control systems were presented for the sake of brevity. The results of analyses for activities in the concrete, structural steel, electrical and piping trades are presented in Table 6.4 through 6.7. It is noted that due to the definition of unit rate productivity in this research, a negative *t*-value represents a positive relationship.

Concrete Trade

In the concrete trade, the automation of only two of the 13 work functions was observed to have significant positive association with normalized unit rate productivity (Table 6.4). Schedule system is significant at 0.03, while quality system is just significant at 0.12. The actual unit rate productivity comparison shows that in concrete trade, the projects with high level automation usage on schedule system and quality systems are associated with 45.1% and 36.6% time savings per installed quantity, respectively (Figure 6.5).

The integration use on four work functions was observed to have a significant positive association with normalized unit rate productivity. Only the integration of cost systems is significant at the 0.05 level. Schedule system appears in the significant list again, but at the 0.1 level rather than the 0.05 level. The actual unit rate productivity comparison shows that the projects with high level automation usage on the four work functions are associated with about 45% to 55% time savings per installed quantity in the concrete trade (Figure 6.6).

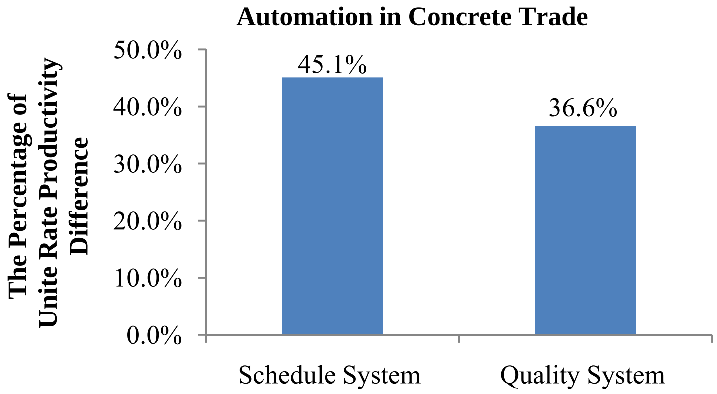

Figure 6.5: Actual Unit Rate Productivity Comparison of Automation Usage in Concrete Trade by Work Function

Table 6.4: Result of *t*-test by Work Function in Concrete Trade

Technology	Work Function	Normalized Unit Rate Productivity Mean			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
		High level Tech	Low level Tech	Difference	F	Sig.	t	Sig.	t	Sig.
Automation	Schedule System ***	2.74 (30)	3.87(39)	-1.13	10.89	0.00	-2.14	0.04	-2.30	0.03
	Quality System *	3.32 (37)	4.25(32)	-0.93	6.31	0.01	-1.62	0.11	-1.59	0.12
Integration	Project Definition *	2.82 (36)	4.25 (10)	-1.43	14.35	0.00	-2.43	-0.02	-1.59	0.14
	Cost System ***	3.09 (23)	4.41 (28)	-1.32	12.16	0.00	-1.97	0.06	-2.10	0.04
	Schedule System **	2.78 (24)	3.69 (30)	-0.91	11.92	0.00	-1.15	0.13	-1.66	0.10
	Facility Start-up *	2.67 (29)	4.25 (10)	-1.58	11.40	0.00	-2.48	0.02	-1.75	0.11

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

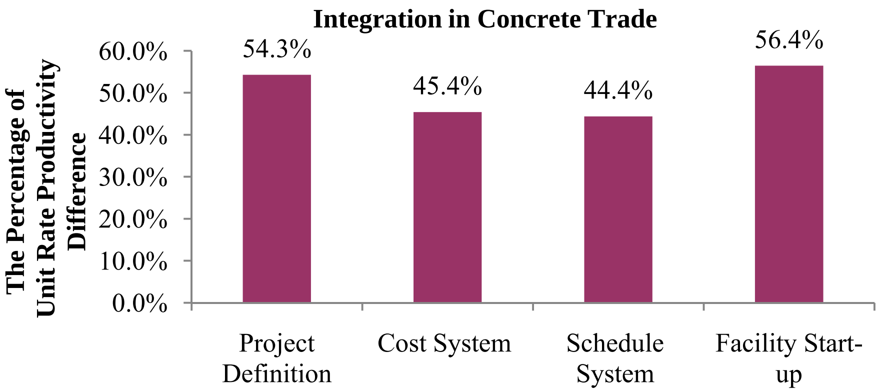

Figure 6.6: Actual Unit Rate Productivity Comparison of Integration Usage in Concrete Trade by Work Function

Structural Steel Trade

The most significant findings among activities in the structural steel trade were presented in Table 6.5. Automation usage on the following five work functions was observed to be statistically significantly related to the improved normalized unit rate productivity among the sampled activities at the 0.05 level: project definition, supply management, quality system, offsite/pre-construction and construction. Automation usage on cost system work function was significant at the 0.15 level. The actual unit rate productivity comparison showed that the projects with high level automation usage on the above work functions were associated with more than 30% time savings per installed quantity in structural steel trade. Specifically, automation usage on supply management system was associated with 51.0% time savings per installed quantity (Figure 6.7).

Integration usage on the following three work functions was observed to have statistically significant relationship (at the 0.05 level) to improved normalized unit rate productivity: supply management, cost system and construction. The integration of project definition and offsite/pre-construction work functions was significant at the 0.1 level. The actual unit rate productivity comparison showed that the projects with high level integration usage on the above five work functions were associated with 20% to 40% time savings per installed quantity. Similar as automation usage, integration usage on supply management ranked No.1 in the five work functions and was associated with 39.2% time savings per installed quantity in the structural steel trade (Figure 6.8).

Table 6.5: Result of *t*-test by Work Function in Structural Steel Trade

Technology	Work Function	Normalized Unit Rate Productivity Mean			Levene's Test for Equality of variances		Equal variances assumed		Equal variances not assumed	
		High level Tech	Low level Tech	Difference	F	Sig.	t	Sig.	t	Sig.
Automation	Project Definition ***	3.33 (20)	5.40 (24)	-2.07	6.27	0.02	-2.96	0.01	-3.06	0.00
	Supply Management ***	3.74 (16)	7.19 (16)	-3.45	7.44	0.01	-4.48	0.00	-4.48	0.00
	Cost System *	3.98 (33)	5.37 (18)	-1.39	18.15	0.00	-1.87	0.07	-1.62	0.12
	Quality System ***	3.74 (40)	5.67 (22)	-1.94	13.28	0.00	-3.13	0.00	-2.73	0.01
	Offsite/pre-construction ***	3.77 (30)	5.72 (14)	-1.95	16.16	0.00	-2.67	0.01	-2.15	0.05
	Construction ***	3.94 (37)	6.09 (7)	-2.16	2.60	0.11	-2.74	0.01	-2.19	0.06
Integration	Project Definition **	3.32 (36)	4.88 (5)	-1.56	0.03	0.87	-1.71	0.10	-1.91	0.11
	Supply Management ***	3.35 (24)	5.27 (21)	-1.92	24.10	0.00	-2.42	0.02	-2.32	0.03
	Cost System ***	3.49 (27)	5.14 (22)	-1.65	18.37	0.00	-2.32	0.03	-2.18	0.04
	Offsite/pre-construction **	3.85 (28)	5.03 (10)	-1.18	0.13	0.72	-1.76	0.09	-2.12	0.05
	Construction ***	3.84 (41)	6.09 (7)	-2.25	1.56	0.22	-2.69	0.01	-2.28	0.06

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

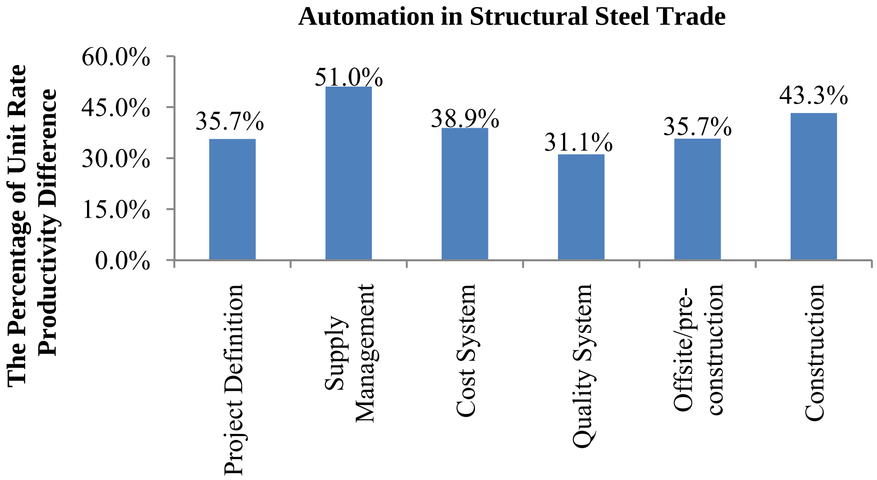

Figure 6.7: Actual Unit Rate Productivity Comparison of Automation Usage in Structural Steel Trade by Work Function

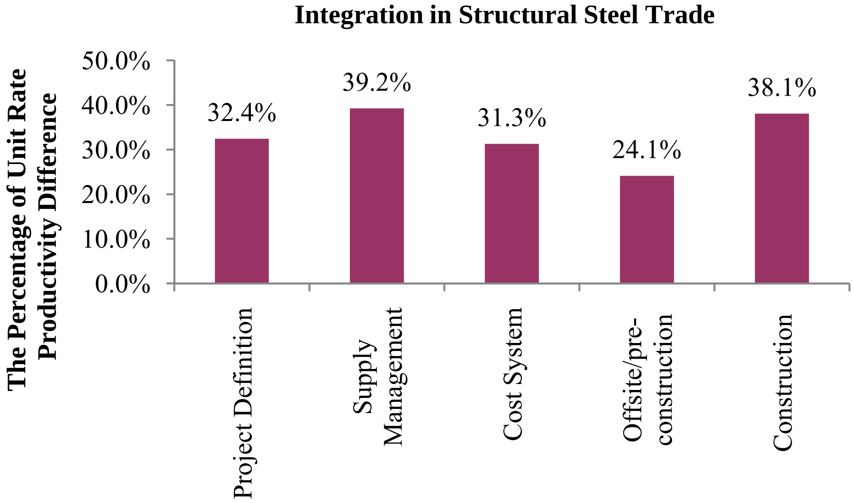

Figure 6.8: Actual Unit Rate Productivity Comparison of Integration Usage in Structural Steel Trade by Work Function

Electrical Trade

Many significant results (Table 6.6) were also observed in the electrical trade. The automation usage on the following two work functions was found to have statistically significant association (at the 0.05 level) with improved normalized unit rate productivity: coordination system and schedule system. Automation usage on communication system and quality system was significant at the 0.1 level, and the automation of supply management was significant at the 0.15 level. The actual unit rate productivity comparison showed that the projects with high level automation usage on the above work functions were associated with 20% to 30% time savings per installed quantity in the electrical trade (Figure 6.9). Automation usage on communication systems ranked No.1 in the five work functions and was associated with 30.0% time savings per installed quantity.

The integration use on the following two work functions was observed to have a statistically significant association (at the 0.05 level) with improved normalized unit rate productivity: communication system and offsite/pre-construction. The integration of coordination system was significant at the 0.1 level, and the integration of cost system and schedule system was significant at the 0.15 level. The actual unit rate productivity comparison showed that the projects with high level integration usage on the above work functions were associated with about 30% to 40% time savings per installed quantity in the electrical trade (Figure 6.10). Similar as automation usage, integration usage on communication systems ranked No.1 in the five work functions and was associated with 39.5% time savings per installed quantity.

Table 6.6: Result of *t*-test by Work Function in Electrical Trade

Technology	Work Function	Normalized Unit Rate Productivity Mean			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
		High level Tech	Low level Tech	Difference	F	Sig.	t	Sig.	t	Sig.
Automation	Supply Management *	3.11 (22)	4.44 (21)	-1.33	1.00	0.32	-1.61	0.12	-1.60	0.12
	Coordination System ***	3.48 (60)	4.84 (25)	-1.35	0.67	0.42	-2.03	0.05	-1.97	0.06
	Communications System **	3.47 (34)	4.84 (25)	-1.37	1.11	0.30	-1.87	0.07	-1.84	0.07
	Schedule System ***	3.04 (48)	4.70 (19)	-1.67	1.54	0.22	-2.38	0.02	-2.22	0.04
	Quality System **	3.65 (52)	4.94 (24)	-1.28	0.92	0.34	-1.85	0.07	-1.79	0.08
Integration	Coordination System **	3.51 (47)	5.76 (11)	-2.25	4.94	0.03	-2.45	0.02	-1.99	0.07
	Communications System ***	3.65 (29)	5.46 (24)	-1.81	2.98	0.09	-2.19	0.03	-2.15	0.04
	Cost System *	3.58 (34)	3.39 (13)	-1.81	0.28	0.60	-2.01	0.05	-1.91	0.07
	Schedule System *	3.22 (33)	4.86 (13)	-1.64	6.65	0.01	-1.79	0.08	-1.55	0.14
	Offsite/pre-construction ***	3.45 (44)	5.77 (9)	-2.32	1.85	0.18	-2.46	0.02	-2.10	0.06

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

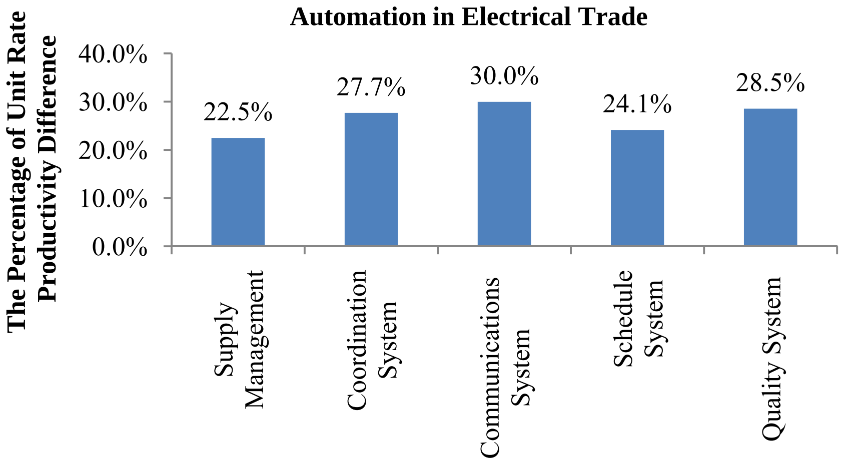

Figure 6.9: Actual Unit Rate Productivity Comparison of Automation Usage in Electrical Steel Trade by Work Function

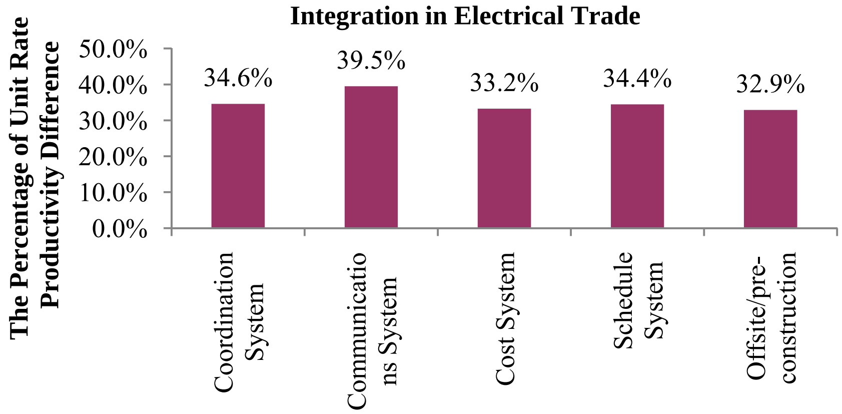

Figure 6.10: Actual Unit Rate Productivity Comparison of Integration Usage in Electrical Steel Trade by Work Function

Piping Trade

The least statistically significant positive results were found for either automation or integration usage in the piping trades (Table 6.7). No work function was significant at the 0.05 level. The automation of quality system was significant at the 0.15 level, and the integration usage on offsite/pre-construction was significant at the 0.1 level. The actual unit rate productivity comparison showed that the projects with high level automation usage on the quality system were associated with 10.2% time savings per installed quantity and the projects with high level integration usage on the Offsite/pre-construction are associated with 14.5% time savings per installed quantity (Figure 6.11). One possible reason for the lack of statistical significance is that the craft workers in the piping trades were not sufficiently trained to apply the new automation and integration technologies. Further data collection and analyses with regards to the workers' characteristics and training level can be helpful to verify the problem.

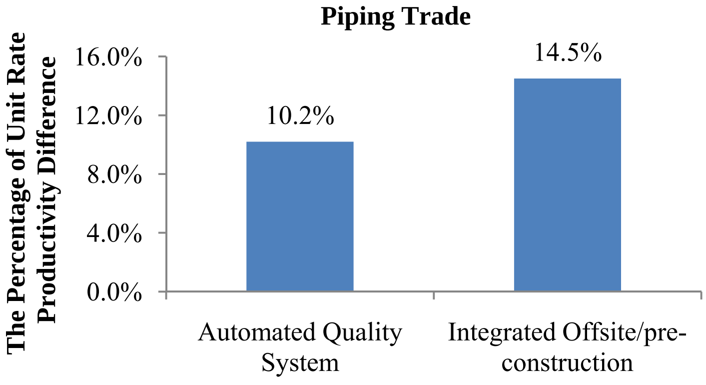

Figure 6.11: Actual Unit Productivity Comparison of Piping Trade by Work Function

Table 6.7: Result of *t*-test by Work Function in Piping Trade

Technology	Work Function	Normalized Unit Rate Productivity Mean			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
		High level Tech	Low level Tech	Difference	F	Sig.	t	Sig.	t	Sig.
Automation	Quality System *	3.83 (59)	4.89 (31)	-1.06	11.07	0.00	-1.63	0.11	-1.48	0.15
Integration	Offsite/pre-construction **	3.64 (44)	5.46 (8)	-1.83	3.04	0.09	-1.73	0.09	-1.37	0.21

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

Relationship Metrics

To summarize the above analyses, matrices were developed to show the statistical strength of the relationship between information technology (Automation and Integration) use on each work function and productivities in all four trades. Relationship matrices for automation and integration are presented in Table 6.8 and Table 6.9, respectively. From the relationship matrices, it can be observed that the most positive relationship were found in the structural steel and electrical trades, while the least positive relationship was found in piping trade. Again, it is emphasized that while analyses may not have found a significant positive result for a given trade and work function, this does not mean that a positive relation does not exist within the industry. As more project data is added to the BM&M data, projects with differing unit rate productivity measures and automation/integration practices will likely identify other positive relations.

Table 6.8: Relationship Matrix: Automation

Work Function	Concrete	Structural Steel	Electrical	Piping
Business Planning & Analysis				
Conceptual Definition & Design				
Project Definition & Facility Design		S		
Supply Management		S	W	
Coordination Systems			S	
Communication Systems			M	
Cost Systems		W		
Schedule Systems	S		S	
Quality Systems	W	S	M	W
Offsite/pre-construction		S		
Construction		S		
As-built Documentation				
Facility Start-up and Life Cycle Support				

Note:
S: Strong relationship, significant at the 0.05 level;
M: Moderate relationship, significant at the 0.1 level;
W: Weak relationship; significant at the 0.15 level;
Blank cell: Positive relationship not observed among sampled projects.

Table 6.9: Relationship Matrix: Integration

Work Function	Concrete	Structural Steel	Electrical	Piping
Business Planning & Analysis				
Conceptual Definition & Design				
Project Definition & Facility Design	W	M		
Supply Management		S		
Coordination Systems			M	
Communication Systems			S	
Cost Systems	S	S	W	
Schedule Systems	M		W	
Quality Systems				
Offsite/pre-construction		M	S	M
Construction		S		
As-built Documentation				
Facility Start-up and Life Cycle Support	W			

Note:
S: Strong relationship, significant at the 0.05 level;
M: Moderate relationship, significant at the 0.1 level;
W: Weak relationship; significant at the 0.15 level;
Blank cell: Positive relationship not observed among sampled projects.

6.2.3 Analyses by Trade and Technology Indices with Actual Unit Rate Productivity Comparison

The author examined differences in unit rate productivity across project use of automation and integration technologies using the indices described by Equations 3.7 and 3.8. The author examined the unit rate productivity among the four trades as well as the productivity among all trades using the normalized unit rate productivity measure. All trades unit rate productivity is a combination of the four trade-specific normalized unit rate productivity datasets, which includes all of the normalized unit rate activity-productivity available in this research combined into one dataset.

The results (Table 6.10, Figure 6.12) indicated that automation usage was positively related to structural steel, electrical and all-trade unit rate productivity, and all of these relationships were significant at the 0.05 level. The results for the concrete and piping trades lacked statistical significance although the relationships were positive. A comparison using actual unit rate productivity measures, as described by Equation 3.9, was also made between projects that had a high versus low usage of automation technologies. The actual unit rate productivity comparison showed that the projects with high level automation usage were associated with 23.3%, 33.9%, 30.3% and 36.4% time savings per installed quantity in the concrete, structural steel, electrical, and piping trades, respectively. The average time saving across the four trades was 30.9% (Figure 6.14).

As indicated in Table 6.11 and Figure 6.13, integration usage was positively related to concrete, structural steel and all-trade unit rate productivity at a statistical significance level of 0.05. The relationship in the electrical trade was significant at the 0.15 level. Again, no statistically significant result was observed in the piping trades, although the relationship was positive. The actual unit rate productivity comparison showed that the projects with high level integration usage were associated with 56.4%, 41.5%, 38.4% and 45.9% time savings per installed quantity in concrete, structural steel, electrical and piping trade, respectively. The average time saving across the four trades is 45.0% (Figure 6.14). While both integration and automation were related with better productivity performance, the analyses suggested that integration had a stronger relationship.

Table 6.10: Results of *t*-test on Automation Index by Trade

Trade	Normalized Unit Rate Productivity			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
	High level Automation	Low level Automation	Difference	F	Sig.	t	Sig.	t	Sig.
Concrete	3.48 (33)	3.89 (37)	-0.40	4.98	0.03	-0.69	0.49	-0.70	0.49
Structural Steel ***	3.74 (40)	5.24 (24)	-1.50	16.91	0.00	-2.42	0.02	-2.14	0.04
Electrical ***	3.65 (52)	5.21 (19)	-1.55	1.51	0.22	-2.04	0.05	-1.91	0.07
Piping	3.96 (53)	4.40 (37)	-0.45	3.97	0.05	-0.71	0.48	-0.69	0.50
All trades ***	3.68 (178)	4.54 (117)	-0.86	20.62	0.00	-2.72	0.01	-2.58	0.01

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

Table 6.11: Results of *t*-test on Integration Index by Trade

Trade	Normalized Unit Rate Productivity			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
	High level Integration	Low level Integration	Difference	F	Sig.	t	Sig.	t	Sig.
Concrete ***	2.91 (33)	4.71 (19)	-1.81	19.90	0.00	-3.12	0.00	-2.61	0.02
Structural Steel***	3.48 (39)	5.30 (10)	-1.82	3.28	0.08	-2.58	0.01	-2.58	0.01
Electrical *	3.28 (48)	5.66 (8)	-2.38	8.15	0.01	-2.36	0.02	-1.73	0.12
Piping	3.82 (52)	5.02 (15)	-1.20	10.59	0.00	-1.39	0.17	-1.12	0.28
All trades ***	3.37 (172)	5.06 (52)	-1.69	28.89	0.00	-4.41	0.00	-3.57	0.00

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

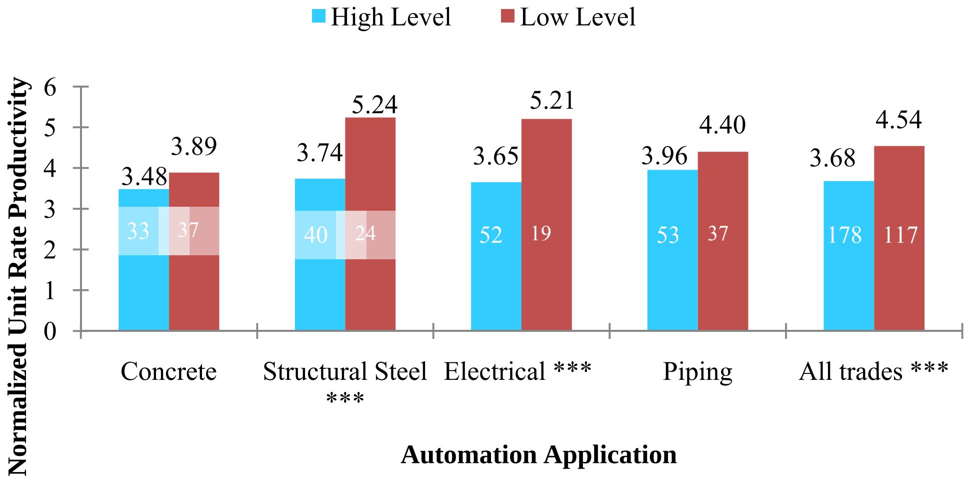

Figure 6.12: Normalized Unit Rate Productivity Comparison by Trade (High Level Automation versus Low Level Automation)

Note: *** denotes significance at 0.05. The numbers on the bars are the sample sizes (unit rate activity productivities)

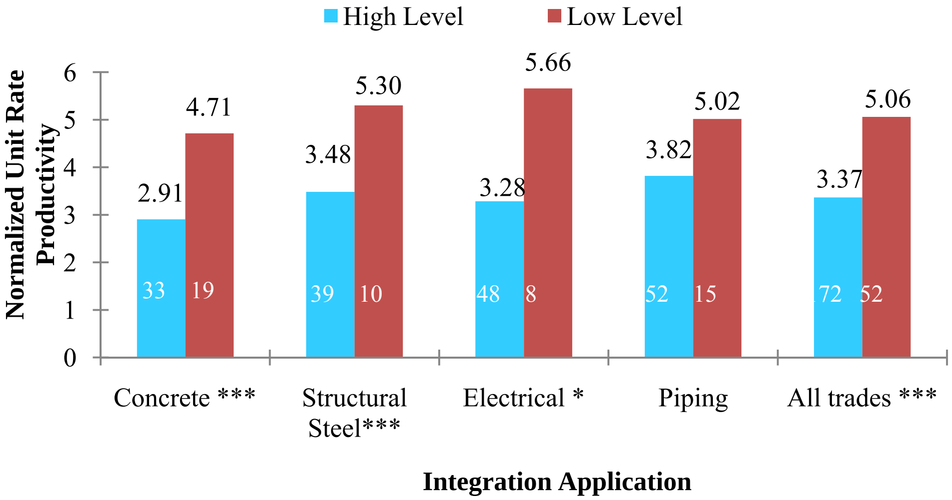

Figure 6.13: Normalized Unit Rate Productivity Comparison by Trade (High Level Integration versus Low Level Integration)

Note: *** denotes significance at 0.05 and * denotes significance at 0.15.
The numbers on the bars are the sample sizes (unit rate activity productivities)

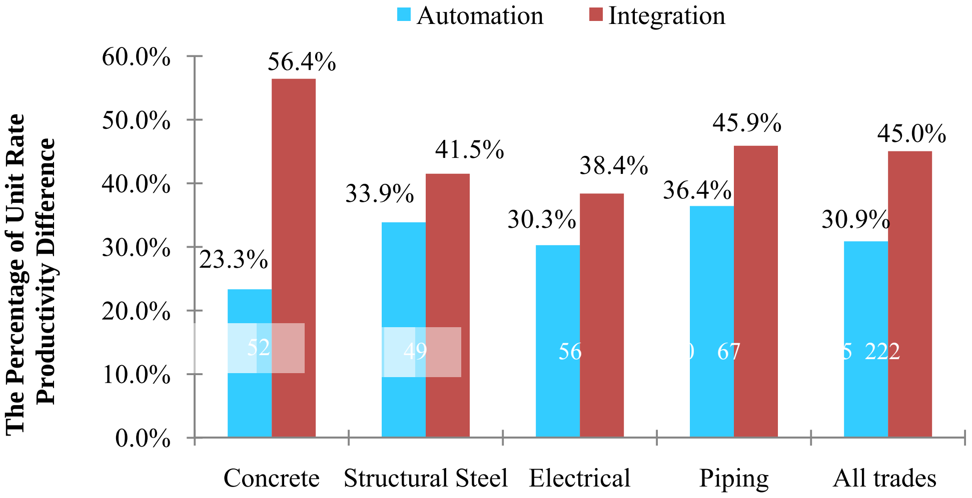

Figure 6.14: Actual Productivity Comparison by Trade

Note: The numbers on the bars are the sample sizes (unit rate activity productivities).

6.2.4 Discussion of Results

Overall, the analyses showed that construction unit rate productivity was positively correlated with the usage of automation and integration technology on the sampled construction projects. The average time savings per installed quantity were observed to be 30.0% and 45.0% when using a high versus a low level of automation and integration, respectively. Few previous research efforts have provided quantifiable information on the extent to which construction productivity is related to automation and integration, thus it is difficult to validate the results in this research directly. However, related results by previous research efforts do exist. For example, Griffis et al. (1995) found that projects using 3D modeling experienced a 65% reduction in rework. Back and Bell (1995) indicated that the material management process exhibited an 85% time savings and a 75% cost savings by fully exploiting electronic data management technologies to enable the capacities of automation and integration. Although it is not the only factor, productivity improvement is one of the most important factors in time savings. Stiroh's research in 2002, not limited to construction, identified that IT had emerged as an appealing candidate to explain the acceleration of U.S. productivity growth in recent years, and his results strengthen that view by establishing a link between IT capital and subsequent productivity growth across U.S. industries. In particular, Stiroh (2002) found that industries that made the largest investments in computer hardware, software, and telecommunication equipment in the 1980's and early 1990's showed larger productivity gains after 1995.

Another important finding in the analysis was that automation and integration uses have different significance in various trades and on different work functions. It is intriguing that piping was the one trade that showed no significant correlation between automation and integration technologies on a project and unit rate productivity (through the analysis of technology indices). Further research is needed to examine this occurrence. Although it is possible that the results lack significance due to sample size, it is also possible that current automation and integration technologies are indeed not helping piping trades become more productive. In the case of the latter explanation, attempting to understand why current automation and integration technologies are not helping is warranted. Meanwhile, O'Connor and Yang (2004) found similar results in their effort using similar automation and integration indices described herein: the association between project performance (schedule and cost) and automation and integration usage are different on various work functions or phases of construction. In particular, O'Connor and Yang (2004) also found that integration technologies had a more significant impact on project performance compared to automation, which mirrors the results presented herein. From the definition of the automation and integration use levels, it can be seen that automation is a prerequisite to integration, and integration is an enhancement of automation. Therefore, it is not strange to observe that integration has a more significant impact on unit rate productivity.

6.2.5 Conclusions

These analyses and discussion based on the sampled large projects contribute to the body of knowledge with regard to the relationship of construction productivity to automation and integration technology in three areas:

1. Information technology has been positively impacting construction productivity and will likely continue to do so in the future;

2. Both the automation and integration of project information systems are related to better construction unit rate productivity performance, and the analyses suggest that a stronger relationship exists with integration; and
3. The effectiveness of automation and integration usage was observed to be different across the four trades. Automation usage was observed to be more positively related to structural steel and electrical productivity, while integration usage was observed to be more positively related to concrete and structural steel productivity.

6.3 Analysis of Small Projects

6.3.1 Descriptive Statistics of Small Projects

The analysis of small projects is not the emphasis of this chapter, but it is a supplement of the analysis of large projects. The reasons are as follows: (1) large projects are more likely to apply information technology due to the long-term life cycle, high investment and project complexity and thus the high volume of information storage, sharing and processing; (2) small projects are not like the large projects, which are often built by large companies and have more complete and reliable data records. Specifically, only 20 projects and 85 activities were included in this chapter's small project analyses. The low sample size in structural steel trade prevented its inclusion in the analyses. The descriptive statistics for the activities' normalized unit productivity were presented in Table 6.12. The means of the normalized activity unit rate productivities from the other three trades ranged from 3.85 for piping to 4.87 for the electrical trade.

Table 6.12: Descriptive Statistics of Small Projects' Normalized Unit Rate Productivity

						95% Confidence Interval of the Mean	
Trade	N（Activities）	Mean	Min	Max	Sta.Dev	Lower	upper
Concrete	21	4.71	1	10	3.35	3.18	6.23
Electrical	28	4.87	1	10	3.48	3.52	6.22
Piping	36	3.85	1	10	3.21	2.76	4.93

Next, the average automation use level for each of the five work functions among the 20 sampled projects was calculated. As shown in Figure 6.15, the average automation use levels on all of the work functions were less than 3.00. The average automation index is 4.46 (on a 0 to 10 scale) with a 95% confidence interval from 3.86 to 5.07, and its distribution among the sampled projects was shown in Figure 6.16. The work function with highest automation use level is procurement, followed by project management. The work function with lowest automation use level is maintenance, followed by construction, and both of them are less than 1.00.

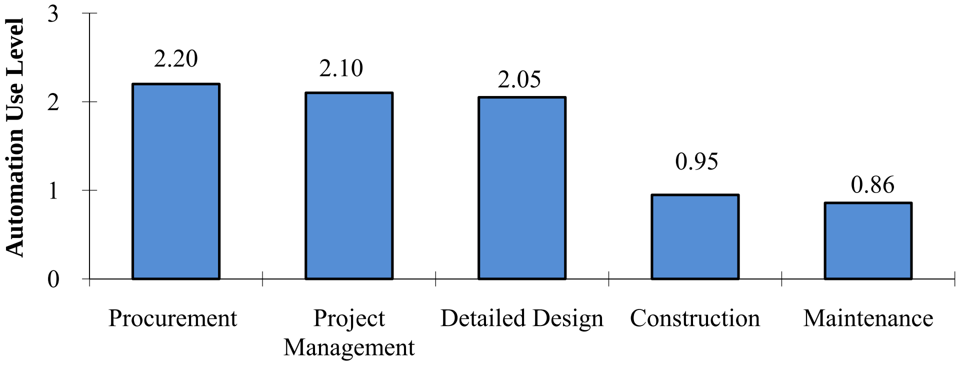

Figure 6.15: The Average Automation Use Level on Each Work Function (Small Projects)

Note: The numbers on the bars are the sample sizes (number of projects)

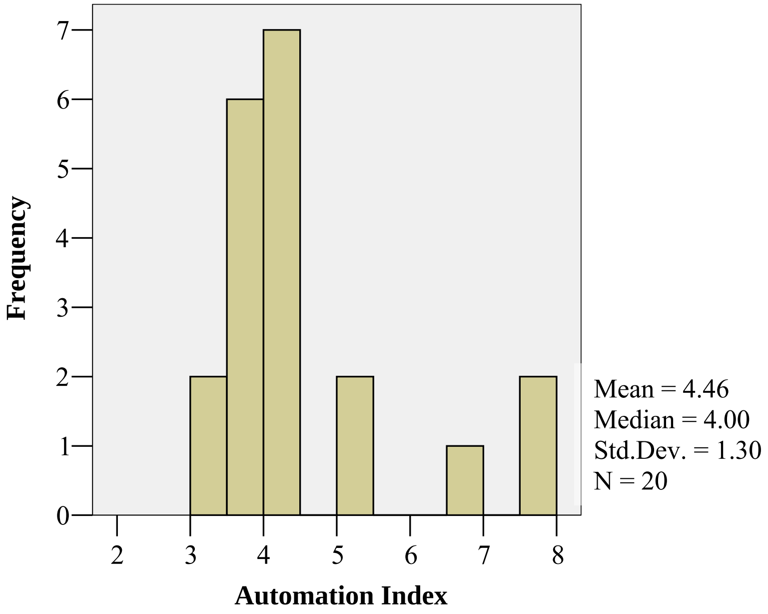

Figure 6.16: The Histogram of Automation Index Distribution for the Sampled Small Projects

The average integration use levels on the 5 work functions are also greater than 3.00 (Figure 6.17), and the average integration index is 4.75 (on a 0 to 10 scale) with a 95% confidence interval from 4.03 to 5.48 (Figure 6.18). The work function with highest integration use level is still procurement, followed by project management. The work function with lowest integration use level is still maintenance, followed by construction, and both of them are less than 1.00.

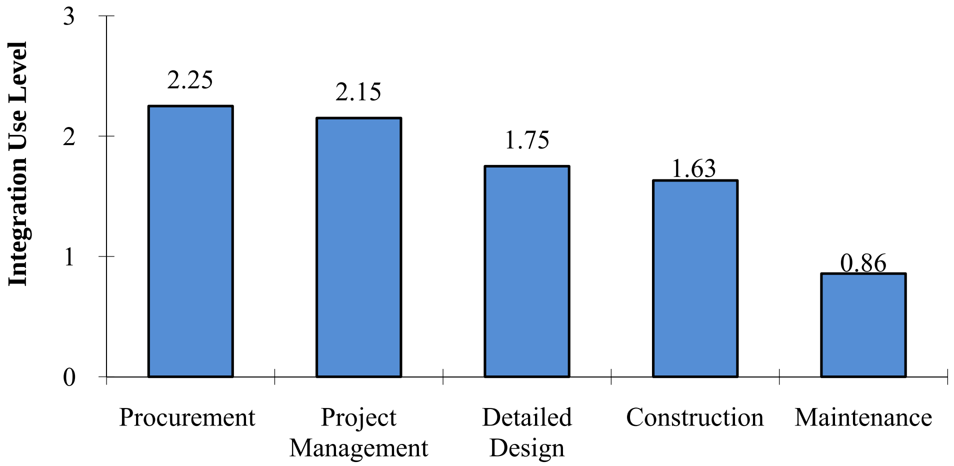

Figure 6.17: The Average Integration Use Level on Each Work Function (Small Projects)

Note: The numbers on the bars are the sample sizes (number of projects)

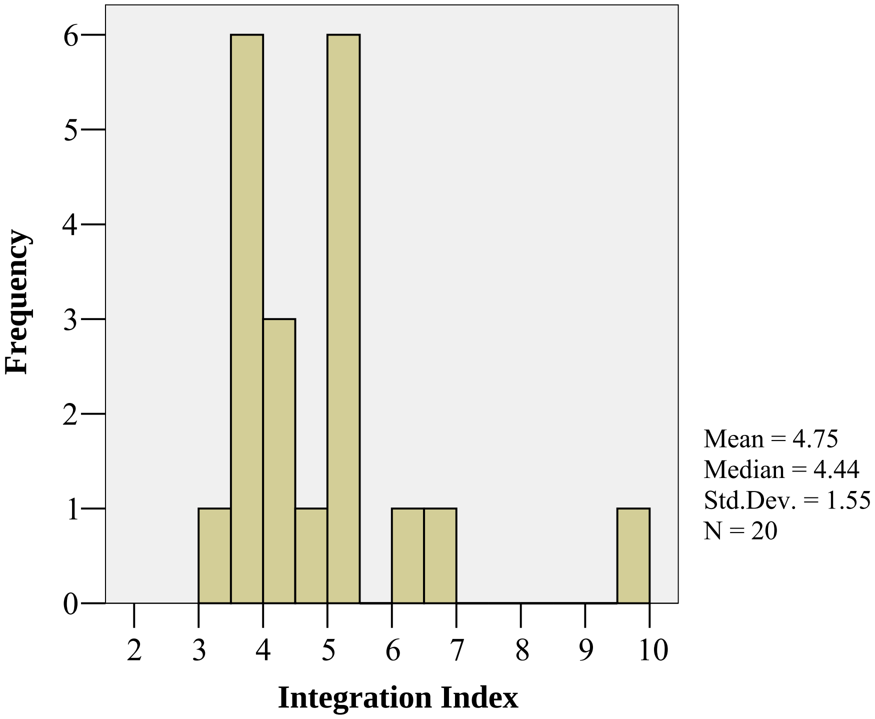

Figure 6.18: The Histogram of Integration Index Distribution for the Sampled Small Projects

Compared with large projects, it can be observed that the average automation and integration indices are relatively lower in small projects (Figure 6.19), and this result is not strange and can be predicted due to the reason mentioned at the beginning of this section.

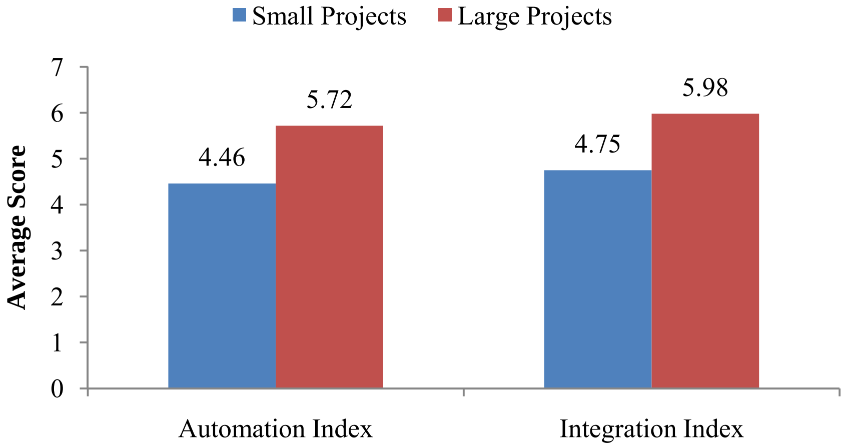

Figure 6.19: The Comparison of Average Automation and Integration Indices between Large Projects and Small Projects

6.3.2 Analyses by Technology Indices with Actual Unit Rate Productivity Comparison

Due to the restriction in sample size, the author cannot perform the analyses by work function and trade for small projects like large projects. Instead, the author calculated the automation and integration indices directly and examined their relationship to normalized all-trade unit rate productivity, followed by the actual unit rate productivity comparison. Therefore, the author did not expect to obtain a comprehensive result through small projects analyses, but just wanted to make the analyses of small projects as a supplement and comparison of the results from large projects.

The results (Table 6.13) indicated that automation usage was positively related to the all-trade unit rate productivity, and this relationship was significant at the 0.15 level. The result for integration usage lacks statistical significance although the relationships were positive. A comparison using actual unit rate productivity measures, as described by Equation 3.9, was also

Table 6.13: Results of t-test on Technology Index and Normalized All-trade Unit Rate Productivity

Technology	Normalized All-trade Unit Rate Productivity			Levene's Test for Equality of Variances		Equal variances assumed		Equal variances not assumed	
	High level Automation	Low level Automation	Difference	F	Sig.	t	Sig.	t	Sig.
Automation*	4.18 (29)	5.61 (34)	-1.43	2.88	0.09	-1.64	0.11	-1.66	0.10
Integration	3.68 (28)	4.54 (36)	-0.58	0.73	0.40	-0.75	0.45	-0.77	0.44

Note: *** denotes significance at 0.05, ** denotes significance at 0.1, and * denotes significance at 0.15.
The numbers in the parentheses are the sample sizes (activity unit rate productivities).

made between projects that had a high versus low usage of automation technologies. The actual productivity comparison showed that the projects with high level automation usage were associated with an average of 41.0% time savings across the three trades. The actual unit rate productivity comparison was not performed for integration usage because of the lack of statistical significance.

6.3.3 Conclusions

The key findings through the small project analyses are as follows:

1. Both the automation use level and integration use level in small projects are lower than large projects;
2. The automation of small projects' information systems are related to better construction unit rate productivity performance, and the analyses suggest that the relationship is statistically significant (at the 0.15 level), but the relationship is not significant for integration usage and unit rate productivity.

These results are not unexpected. Small projects are less complex and thus have less information exchange and data processing than large projects, therefore the requirement for automation on each work function and integration between different work functions are not as strong as large projects. In addition, because integration can be considered as an enhanced feature of automation, it may not realize its potential to improve labor productivity as automation in small projects with low requirement of information exchange.

6.4 Factor Analysis

The factor analysis was performed for only large projects. As mentioned before, the purpose of this factor analysis is to discover simple patterns of relationships among the 13 work functions of large projects. In other words, it intends to find if the work functions can be explained largely or entirely in terms of a much smaller number of variables. It should be noted that the patterns of relationships among the 13 work functions could be same, similar or different on automation usage and integration usage.

6.4.1 Factor Analysis of Work Functions in Regard to Automation Usage

To technically examine the adequacy of factor analysis, Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were examined. The KMO statistic varies between 0 and 1, with 0 indicating diffusion in the pattern of correlations among the 13 work functions, and 1 indicating that patterns of correlations are relatively compact. A KMO statistic greater than 0.5 is usually considered to be acceptable. Bartlett's measure tests the hypothesis that the original correlation matrix is an identity matrix. Bartlett's test of sphericity should be significant in order to use factor analysis technique. For the work functions in regard to automation usage, the KMO statistic is 0.84 and Bartlett's test is extremely significant (p<0.01), and thus factor analysis is appropriate to identify the underlying structure of the work functions (Table 6.12).

Table 6.14: KMO and Bartlett's Test for Factor Analysis (Work Functions in Regard to Automation Usage)

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.84
Bartlett's Test of Sphericity	Approx. Chi-Square	329.60
	Degree of freedom	78
	Significance	<0.01

Principal Factor Analysis

Figure 6.20 is the scree plot, and the "elbow" appears on the second factor. As mentioned before, the number of data points above the "elbow" is usually the number of the latent factors to retain, so only one factor should be retained based on the scree plot. However, Kaiser Rule would retain two latent factors with eigenvalues greater than 1.0. Since SPSS makes it possible and convenient to repeat the factor analysis process, factors analyses were run with different numbers (1 or 2) of latent factors extracted. Finally, a solution with 2 factors which was generated by principal axis factoring with Varimax rotation provided best interpretability and explains a major percentage of variance. The output of factor analysis was presented as Appendix C.

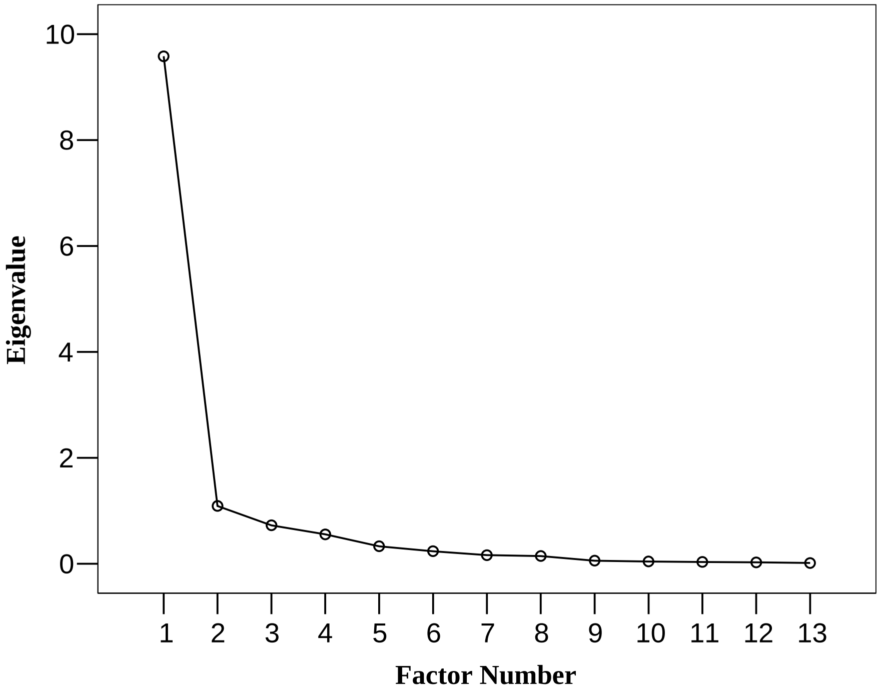

Figure 6.20: Scree Plot for the Latent Factors in Regard to Automation Use

Table 6.15 showed the eigenvalues associated with latent factors before extraction, after extraction, and after rotation. Each eigenvalue represents the variance explained by the corresponding latent factor. After extraction, two latent factors accounted for 78.8% of the variance. In other words, after extraction, the two latent factors could explain nearly 80% of the original information of 13 work functions. Rotation has the effect of optimizing the factor structure and leveling the variance explained by individual latent factors. As shown in Table 6.15, the first latent factor explained 72.22% of the total variance before rotation, which was much higher than the second latent factor, which explained only 6.57% of the total variance. After rotation, the total variance explained by the first latent factor dropped to 46.79%, and accordingly the variance explained by the second latent factors increased to 32.00%.

Table 6.15: Total Variance of Frequency Factors Explained by Latent Factors (Automation)

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	9.583	73.714	73.714	9.389	72.220	72.220	6.083	46.789	46.789
2	1.091	8.391	82.106	0.854	6.566	78.786	4.160	31.997	78.786
3	0.726	5.582	87.688						
4	0.554	4.263	91.951						
5	0.329	2.534	94.485						
6	0.236	1.817	96.302						
7	0.162	1.248	97.550						
8	0.145	1.118	98.668						
9	0.058	0.448	99.116						
10	0.042	0.324	99.440						
11	0.034	0.258	99.698						
12	0.025	0.195	99.893						
13	0.014	0.107	100						

Note: Extraction Method: Principal Axis Factoring.

Rotation

Although different rotation methods could be used, the Varimax method generated an easy interpreted group of latent factors as shown in Table 6.16. Factor loading ranges from 0.0 to 1.0, which represents the correlation between the work functions and the latent factors. In Table 6.16, dominant factor loadings, which are the largest factor loadings of any work function and generally larger than 0.5, were highlighted in bold. The squared factor loading is the percent of variance in a work function explained by the corresponding latent factor.

Table 6.16: Rotated Factor Matrix for Work Functions in Regard to Automation Usage

Work Functions	Latent Factors		Extraction Communities
	1	2	
WF1:Business Planning & Analysis	0.216	**0.779**	0.654
WF2:Conceptual Definition & Design	0.533	**0.795**	0.916
WF3:Project Definition & Facility Design	0.355	**0.802**	0.768
WF4:Supply Management	**0.630**	0.341	0.513
WF5:Coordination Systems	**0.722**	0.589	0.868
WF6:Communication Systems	**0.747**	0.568	0.881
WF7:Cost Systems	**0.898**	0.268	0.878
WF8:Schedule Systems	**0.867**	0.377	0.895
WF9:Quality Systems	**0.824**	0.404	0.842
WF10:Offsite/pre-construction	**0.629**	0.499	0.644
WF11:Construction	**0.770**	0.457	0.802
WF12:As-built Documentation	0.529	**0.746**	0.836
WF13:Facility Start-up and Life Cycle Support	**0.802**	0.319	0.746

Note: The dominant factor loadings highlighted by bold.

Extraction communality is the squared multiple correlation for a work function using the latent factors as predictors. Specifically, the communality measures the percent of variance in a given variable explained by all the latent factors jointly and can be interpreted as an indicator to measure the reliability of the factor analysis. Table 6.16 also presented extraction communality of the principal axis factoring. For example, the two latent factors accounted for 65.4% of variance of the automation usage on business planning and analysis.

For 10 of the 13 work functions, the two latent factors explained over 70% of their variance. Only three work functions, including business planning and analysis, supply management and offsite/pre-construction had less than 70% but more than 50% of their variance explained by the two latent factors. Therefore, the factor analysis was very successful to reduce the number of work functions while retaining the majority of the original information.

Interpretation

The purpose of rotation is to help interpret the latent factors. The work functions with dominant factor loadings (close to 1.0) determine the nature of the latent factors. Table 6.16 indicated all of the 13 work functions had obvious dominant factor loadings. In order to interpret the latent factors, Table 6.17 listed the work functions by their dominant factor loadings on the two latent factors. Supply management, coordination systems, communication systems, cost systems, schedule systems, quality systems, offsite/pre-construction and construction loaded more substantially on latent factor 1 than the rest four variables. Therefore, latent factor 1 can be described as *Site Management Systems.* Business planning & analysis, conceptual planning & design, project definition & facility, and as-built documentation loaded more on the second latent factor. Therefore, latent factor 2 can be labeled as *Front End Planning and Engineering Systems.* It is noted that the interpretation of the latent factors are very subjective and highly relied on the researcher's knowledge and understanding.

Discussion on the Latent Factors

A product of factor analysis was the factor scores, which can be used for further analyses, such as regression analysis, in place of the original 13 work functions. Factor scores are composite measures that can be computed for each latent factor from the factor score coefficient matrix. Table 6.18 presented the factor score coefficient matrix for the factor analysis on the work functions in regard to automation usage. The coefficients were highlighted when the corresponding factors have dominant factor loadings as discussed above.

Table 6.17: Definition of the Latent Factors for Work Functions in Regard to Automation Usage

Latent Factor	Work Functions
Factor 1: **Site Management Systems**	Supply Management
	Coordination Systems
	Communication Systems
	Cost Systems
	Schedule Systems
	Quality Systems
	Offsite/pre-construction
	Construction
	Facility Start-up and Life Cycle Support
Factor 2: **Front End Planning and Engineering Systems**	Business Planning & Analysis
	Conceptual Definition & Design
	Project Definition & Facility Design
	As-built Documentation

Table 6.18: Factor Score Coefficient Matrix for Work Functions in Regard to Automation Usage

Work Functions	Latent Factors	
	Site Management Systems	**Front End Planning and Engineering Systems**
WF1:Business Planning & Analysis	-0.299	**0.502**
WF2:Conceptual Definition & Design	-0.078	**0.257**
WF3:Project Definition & Facility Design	-0.165	**0.348**
WF4:Supply Management	**0.206**	-0.142
WF5:Coordination Systems	**0.072**	0.066
WF6:Communication Systems	**0.077**	0.060
WF7:Cost Systems	**0.256**	-0.183
WF8:Schedule Systems	**0.202**	-0.105
WF9:Quality Systems	**0.189**	-0.091
WF10:Offsite/pre-construction	**0.052**	0.074
WF11:Construction	**0.146**	-0.037
WF12:As-built Documentation	-0.065	**0.236**
WF13:Facility Start-up and Life Cycle Support	**0.247**	-0.177

For example, the factor score for latent factor 1 can be calculated by the following Equation 6.1:

$$F_1 = r_{1\_1} \times \frac{(WF1 - Mean1)}{Stdev1} + r_{1\_2} \times \frac{(WF2 - Mean2)}{Stdev2} + \cdots + r_{1\_13} \times \frac{(WF13 - Mean13)}{Stdev13} \qquad (6.1)$$

where:

WF*i* is the automation use score of the *i*th work function on a project;

Mean*i* is the mean value of automation use score of the *i*th work function across all sampled projects;

Stdev*i* is the standard deviation of automation use score of the *i*th work function; and

r_{1_i} is the factor score coefficient in Table 6.16. For example, $r_{1\_1} = 0.168$, $r_{1\_2} = -0.812$, … , and $r_{1\_13} = 0.162$.

Table 6.19 listed the weighting of the work functions on their corresponding latent factors. The weighting shows how much each work function contributed to the latent factors. For example, the average increase in *Site Management Systems* was 0.206 standard deviation increase in supply management while keeping other work functions constant. All of the work functions were ordered based on their weighting on the latent factors. Therefore, cost systems appeared to be the most important to *Site Management Systems* and business planning and analysis was the most important factor for *Front End Planning and Engineering Systems*.

Table 6.19: Weighting of Work Functions on the Latent Factors in Regard to Automation Usage

Factor	Weighting
Site Management Systems	
WF7: Cost Systems	0.256
WF13: Facility Start-up and Life Cycle Support	0.247
WF4: Supply Management	0.206
WF8: Schedule Systems	0.202
WF9: Quality Systems	0.189
WF11: Construction	0.146
WF6: Communication Systems	0.077
WF5: Coordination Systems	0.072
WF10: Offsite/pre-construction	0.052
Front End Planning and Engineering Systems	
WF1: Business Planning & Analysis	0.502
WF3: Project Definition & Facility Design	0.348
WF2: Conceptual Definition & Design	0.257
WF12:As-built Documentation	0.236

Factor scores can be automatically calculated in SPSS. However, the factor scores provided by SPSS are not on the same scale, which makes it difficult to understand and compare the latent factors. Following the methodology described in chapter three, the factor scores were normalized with 5 indicating the maximum automation, and 1 indicating the minimum automation. The proportional minimum, mean, maximum scores for the two latent factors were presented in Table 6.20. It can be observed that the mean score of *Site Management Systems* was a litter higher than *Front End Planning and Engineering Systems*, which means the automation use level was higher on the first latent factor than on the second latent factor on the sampled projects.

Table 6.20: Latent Factors Scale Scores for Work Functions in Regard to Automation Usage

Factor Scale	Minimum	Mean	Maximum
Site Management Systems	2.39	3.25	4.30
Front End Planning and Engineering Systems	1.78	3.00	3.86

6.4.2 Factor Analysis of Work Functions in Regard to Integration Usage

Similarly, a factor analysis using principal axis factoring with Varimax rotation was also performed on the 13 work functions in regard to integration usage. As shown in Table 6.21, both the Kaiser-Meyer-Olkin Measure of Sampling Adequacy test (0.58) and Bartlett's Test of Sphericity (significance<0.01) are significant, which indicates that the factor model is appropriate. According to the analysis, two latent factors were retained and they explained 90.34% of the total variance (Table 6.22).

Table 6.21: KMO and Bartlett's Test for Factor Analysis (Work Functions in Regard to Integration Usage)

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.58
Bartlett's Test of Sphericity	Approx. Chi-Square	371.59
	df	78
	Sig.	<0.01

Again, the factor loadings and extraction communities were presented in the rotated factor matrix (Table 6.23). The dominant factor loadings were highlighted by bold. The extractor communities indicated that for all of the 13 work functions, the two latent factors could explain over 75% of their total variance. It suggested that factor analysis was very successful to reduce the number of work functions while retaining the majority of included information. SPSS output of the factor analysis for the work functions in regard to integration usage were also included in Appendix C.

Table 6.22: Total Variance of Frequency Factors Explained by Latent Factors (Integration)

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	10.701	82.316	82.316	10.701	82.316	82.316	7.028	54.059	54.059
2	1.043	8.022	90.338	1.043	8.022	90.338	4.716	36.279	90.338
3	0.422	3.243	93.582						
4	0.296	2.276	95.857						
5	0.202	1.550	97.408						
6	0.121	0.931	98.338						
7	0.073	0.561	98.899						
8	0.069	0.532	99.431						
9	0.045	0.347	99.777						
10	0.014	0.105	99.882						
11	0.009	0.072	99.954						
12	0.006	0.044	99.998						
13	0.000	0.002	100						

Note: Extraction Method: Principal Axis Factoring.

Table 6.23: Rotated Factor Matrix for Work Functions in Regard to Integration Usage

Work Functions	**Latent Factors**		**Extraction Communities**
	1	**2**	
WF1:Business Planning & Analysis	0.352	**0.909**	0.950
WF2:Conceptual Definition & Design	0.437	**0.857**	0.926
WF3:Project Definition & Facility Design	0.607	**0.744**	0.923
WF4:Supply Management	**0.758**	0.460	0.786
WF5:Coordination Systems	**0.847**	0.400	0.878
WF6:Communication Systems	**0.776**	0.567	0.925
WF7:Cost Systems	**0.898**	0.327	0.914
WF8:Schedule Systems	**0.810**	0.438	0.848
WF9:Quality Systems	**0.894**	0.322	0.903
WF10:Offsite/pre-construction	**0.733**	0.561	0.852
WF11:Construction	**0.837**	0.480	0.930
WF12:As-built Documentation	**0.909**	0.382	0.973
WF13:Facility Start-up and Life Cycle Support	0.352	**0.902**	0.938

Note: The dominant factor loadings are highlighted by bold.

The weights of work functions in regard to integration usage on the latent factors were presented in Table 6.24. The interpretation of each latent factor was determined by the dominant factors. The first latent factor involved all the work functions of project management, construction and as-built documentation. Therefore, the first latent factor can also be interpreted as *Site Management Systems.* The second latent factor involved work functions of planning, design and life cycle support and this factor can also be interpreted as *Front End Planning and Engineering Systems*.

Table 6.24: Weighting of Work Functions on the Latent Factors in Regard to Integration Usage

Factor	Weighting
Site Management Systems	
WF9:Quality Systems	0.242
WF7:Cost Systems	0.242
WF12:As-built Documentation	0.224
WF5:Coordination Systems	0.190
WF8:Schedule Systems	0.158
WF11:Construction	0.152
WF4:Supply Management	0.127
WF6:Communication Systems	0.090
WF10:Offsite/pre-construction	0.074
Front End Planning and Engineering Systems	
WF1:Business Planning & Analysis	0.425
WF13:Facility Start-up and Life Cycle Support	0.420
WF2:Conceptual Definition & Design	0.356
WF3:Project Definition & Facility Design	0.213

Following the same methodology as discussed earlier, after SPSS produced the factor scores, the author normalized the scores to a 1 to 5 scale level, where 1 means minimum integration and 5 means maximum integration. The minimum, mean, maximum scale scores for the two latent factors were presented in Table 6.25. It can be observed that the mean score of *Site Management Systems* was a litter higher than *Front End Planning and Engineering Systems*, which means the integration use level was higher on contractors than on owners and designer for the sampled projects.

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Table 6.25: Latent Factors Scale Scores for Work Functions in Regard to Integration Usage

Factor Scale	Minimum	Mean	Maximum
Site Management Systems	2.28	3.28	3.91
Front End Planning and Engineering Systems	2.03	2.98	4.21

6.4.3 Conclusions

In summary, the factor analysis successfully identified the simple pattern of relationships among the 13 work functions in regard to their automation and integration use without losing much variance or information they had. The following is the key findings through factor analysis.

1. Two latent factors were extracted from the 13 work functions in regard to both automation use and integration use, and they accounted for 78.8% and 90.3% of total variance in the 13 work functions, respectively.
2. The two latent factors were *Site Management Systems* and *Front End Planning and Engineering Systems*, but their composition has minor difference in regards to automation use and integration use. The average automation and integration use levels on the first factor was higher than the second factor.

6.5 Multiple Regression Analysis

So far, this dissertation research has identified the relationship of between construction unit rate productivity and the automation and integration usage by work functions and trades, and the factor analysis identified the latent factors representing the correlation of all work functions. The next step is to find the area where the application of automation and integration could improve the construction unit rate productivity with the largest possibility. This step can be achieved through the multiple regression analysis. The SPSS output for multiple regression analysis was also presented in Appendix C. It should be noted that it is not valid to include the automation factors and integration factors in any regression model at the same time, because integration can be considered as an enhanced feature of automation and thus they are not independent. Therefore, it is also not valid to compare automation and integration features' relative importance through regression. This comparison can only be made through *t*-test combined with actual unit rate productivity comparison as discussed in Section 6.2, where the analyses for automation and integration are separated.

6.5.1 Automation Usage versus Normalized Unit Rate Productivity

Concrete Trade

Through the curve estimation provided by SPSS, the author could find what kind of model was best fitted with the relationship between individual latent factors and the normalized unit rate productivity. In the analysis of construction trade, it was found that the relationship was best fitted with a quadratic model since its R^2 was greater than linear, cubic, power, logarithmic and exponential models. However, in comparison to the linear model, the improvement of R^2 by using the best fitted models was not substantial. Therefore, for the purpose of simplifying the model and facilitating the comparison across the latent factors, a linear model was chosen for the regression. Table 6.26 listed the regression model of latent factors with concrete unit rate productivity. Similar to previous analyses in this chapter, a negative regression coefficient indicates a positive impact of automation usage. As shown in Table 6.26, only the regression coefficient of *Site Management Systems* (Model A) was statistically significant at the 95% confidence level. The R^2 of this model was 8.4%, which indicated 8.4 percent of variance can be explained by this regression model. For *Front End Planning and Engineering Systems* (Model B), its regression coefficient was not significant at the 95% confidence level and the model's F value was pretty low, which indicated this regression model lacked goodness of fit. As for Model C, which included both latent factors in the regression, the value of R^2 was not higher than Model A, and its F value did not indicate significance at the 95% confidence level. Therefore, Model A was best fitted with the impact of automation usage on concrete activity unit rate productivity.

Table 6.26: Regression of Latent Factors for Normalized Concrete Unit Rate Productivity (Automation Usage)

Model	Constant	Independent Variables		F [13]	R^2 [14]	Adjusted R^2 [15]
		Site Management Systems	Front End Planning and Engineering Systems			
A	7.18* (4.24)	-1.18* (-2.29)		5.23*	0.08	0.07
B	3.62* (1.78)		-0.08 (-0.13)	0.02	0.00	-0.02
C	7.31* (2.86)	-1.17* (-2.26)	-0.05 (-0.07)	2.57	0.08	0.05

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

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[13] The F value used to test statistical significance in regression is the ratio of variance explained by regression versus the unexplained variance. Specifically, $F = \frac{Mean\ Square\ Between}{Mean\ Square\ Within}$

[14] R^2 is the fraction of the variance in the data that is explained by a regression, which is used as the coefficient of determination.

[15] Adjusted R2 takes into account the number of independent variables and the number of observation included in a regression.

$$\text{adjusted}R^2 = R^2 - \frac{k-1}{n \times k} \times (1 - R^2)$$

Structural Steel Trade

For structural steel trade, it was found that the relationship between the automation usage on the two latent factors and normalized unit rate productivity was best fitted with a logarithmic model, but the linear model ranked second and the improvement of R^2 by using the logarithmic model was not substantial. Therefore, a linear model was chosen again for the regression analysis in structural steel trade. Table 6.27 listed the regression model of each latent factor with normalized structural steel unit rate productivity. All latent factors' the regression coefficients were statistically significant at the 95% confidence level. *Site Management Systems* (Model A) had a larger R^2 of 7.9% than *Front End Planning and Engineering Systems* (Model B, 6.9%). Again, Model C included both latent factors in the regression, and its R^2 of 20.4% was much larger than the two models with only one latent factor, and its F value was also significant at the 95% confidence level. Therefore, Model C was the best model, which indicated that the automation usage on both latent factors had significantly positive impact on structural steel unit rate productivity.

Table 6.27: Regression of Latent Factors for Normalized Structural Steel Unit Rate Productivity (Automation Usage)

Model	Constant	Independent Variables		F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems			
A	7.30* (3.94)	-1.05* (-1.99)		3.94*	0.07	0.05
B	7.83* (3.96)		-1.35* (-2.13)	4.54*	0.08	0.06
C	14.42* (4.87)	-1.47* (-2.86)	-1.84* (-2.97)	6.66*	0.20	0.17

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

Since there were two latent factors (independent variables) included in Model C, it was important to identify which factor had the greater impact on structural steel unit rate productivity. As mentioned in Chapter three, it was not reasonable to rank the latent factors (independent variables) based on the magnitude of the regression coefficients, since the latent factors had different standard deviations (Table 6.28). Therefore, the standardized regression coefficient was used to compare the latent factors' impact on the normalized unit rate productivity in structural steel trade because it refers to the predicted increase in standard deviation units of normalized unit rate productivity per standard deviation increase in the latent factors. Table 6.28 listed the standardized regression coefficient for regression model C in Table 27. The average increase in normalized structural steel unit rate productivity was 0.37 unit of standard deviation per unit of standard deviation increase in *Site Management Systems* while holding the other latent factor constant, while the average increase in the unit rate productivity was 0.38 standard deviation unit per standard deviation unit increase in *Front End Planning and Engineering Systems*. Therefore, the two factors' impact on structural steel unit rate productivity was similar.

Table 6.28: Standardized Regression Coefficient for Model C in Table 6.25

Factor Scale	Standardized Regression Coefficient	Average Factor Scale Score	Standard Deviation
Site Management Systems	-0.37	3.25	0.52
Front End Planning and Engineering Systems	-0.38	3.00	0.62

Electrical Trade

For electrical trade, the author chose the linear regression model for the same reason as above. Table 6.29 listed the regression model of each latent factor with electrical unit rate productivity. Only the regression coefficient of *Site Management Systems* (Model A) was statistically significant at the 95% confidence level. The R^2 of this model was 12.8%, which indicated 12.8 percent of variance can be explained by this regression model. For *Front End Planning and Engineering Systems* (Model B), its regression coefficient was not significant at the 95% confidence level and the model's F value is low, which indicated this regression model lacked goodness of fit. As for Model C, which included both latent factors in the regression, the value of R^2 was the same as Model A, and its F value also indicated significance at the 95% confidence level. But given the same R^2, the model with less independent variable was simpler and thus better. Therefore, Model A was best fitted with the impact of automation usage on electrical unit rate productivity.

Table 6.29: Regression of Latent Factors for Normalized Electrical Unit Rate Productivity (Automation Usage)

Model	Constant	Independent Variables			F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems				
A	11.18* (4.20)	-2.14* (-2.92)			8.51*	0.13	0.11
B	-0.00* (2.21)		1.13* (1.60)		2.57	0.04	0.03
C	10.95* (2.15)	-2.11* (-2.37)	-1.84 (0.05)		6.66*	0.13	0.10

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

Piping Trade

For piping trade, the linear regression model was also chosen and the result was shown in Table 6.30. It can be observed that no regression coefficients and F values were significant at the 95% confidence level in all of the three models, which indicated that significant impact of automation use on piping trade could not be observed for the sample projects in this research.

Table 6.30: Regression of Latent Factors for Normalized Piping Unit Rate Productivity (Automation Usage)

Model	Constant	Independent Variables		F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems			
A	-1.10 (-0.36)	1.32 (1.44)		2.06	0.07	0.04
B	4.61 (1.09)		0.44 (0.32)	0.1	<0.01	-0.03
C	1.22 (0.26)	1.46 (1.54)	-0.92 (-0.67)	1.23	0.13	0.10

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis.

Total Trades

For the total trades, the author chose the linear regression model as well. As shown in Table 6.31, only the regression coefficient of *Site Management Systems* (Model A) was statistically significant at the 95% confidence level. The R^2 of this model was 3.5%, which indicated 3.5 percent of variance could be explained by this regression model. For *Front End Planning and Engineering Systems* (Model B), its regression coefficient was not significant at the 95% confidence level and the model's F value indicated lack of goodness of fit. For Model C, which included both latent factors in the regression, the value of R^2 was the approximate to Model A, and its F value also indicated significance at the 95% confidence level. Therefore, Model A was best fitted with the impact of automation usage on all-trade unit rate productivity.

Table 6.31: Regression of Latent Factors for Normalized All-trade Unit Rate Productivity (Automation Usage)

Model	Constant	Independent Variables		F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems			
A	6.40* (5.86)	-0.86* (-2.72)		7.40*	0.04	0.03
B	3.34* (2.83)		0.04 (0.11)	0.01	<0.01	-0.01
C	6.86* (3.95)	-0.88* (-2.73)	-0.13 (-0.34)	3.74*	0.04	0.03

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

6.5.2 Integration Usage versus Normalized Unit Rate Productivity

Similarly, regression analyses were performed to identify the impact of the latent factors and also linear regression models were chosen. The results were presented through Tables 6.32 to 6.37.

The result for concrete trade was presented in Table 6.32 and Table 6.33. Model C, which included both latent factors, had the largest R^2 of 19% in the three models (Table 6.32). The F value of 5.11 was significant at the 95% confidence level and indicated the model's goodness of fit. The two latent factors' regression coefficients were also significant at the 95% confidence level, which indicated that the integration usage on both latent factors had significantly positive impact on concrete unit rate productivity. Through the comparison of standardized regression coefficients, the integration usage on *Front End Planning and Engineering Systems* had greater impact on concrete unit rate productivity than the *Site Management Systems* (Table 6.33).

Table 6.32: Regression of Latent Factors for Normalized Concrete Unit Rate Productivity (Integration Use)

Model	Constant	Independent Variables		F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems			
A	7.06* (3.30)	-1.10 (-1.70)		2.90	0.06	0.04
B	7.79* (4.10)		-1.35* (-2.31)	5.35*	0.11	0.09
C	12.46* (4.34)	-1.29* (-2.11)	-1.60* (-2.63)	5.11*	0.19	0.15

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

Table 6.33: Standardized Regression Coefficient for Model C in Table 6.32

Factor Scale	**Standardized Regression Coefficient**	**Average Factor Scale Score**	**Standard Deviation**
Site Management Systems	-0.29	3.28	0.52
Front End Planning and Engineering Systems	-0.36	2.98	0.62

The result for structural steel trade was presented in Table 6.34. Only the regression coefficient of *Site Management Systems was* significant at the 95% confidence level. In the three models, Model A was the best fitted model. Its F value of 12.46 was also significant at 95% confidence level and indicated the model's goodness of fit. The value of R^2 indicated 24% of variance can be explained by this regression model. The result for electrical trade was similar to structural steel trade (Table 6.35). Model A, which included only the *Site Management Systems*, was the best fitted model. The F value and regression coefficient were significant at the 95% confidence level. The value of R^2 indicated 16% of variance can be explained by this regression model.

Table 6.34: Regression of Latent Factors for Normalized Structural Steel Unit Rate Productivity (Integration Use)

Model	Constant	Independent Variables			F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems				
A	10.58* (5.23)	-2.09* (-3.53)			12.46*	0.24	0.22
B	-0.42 (-0.19)		1.28 (1.78)		3.17	0.08	0.05
C	9.03* (2.37)	-1.95* (-2.94)	0.35 (0.48)		6.22*	0.25	0.21

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

Table 6.35: Regression of Latent Factors for Normalized Electrical Unit Rate Productivity (Integration Use)

Model	Constant	Independent Variables			F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems				
A	14.82* (3.77)	-3.15* (-2.89)			8.34*	0.16	0.14
B	6.39 (1.53)		-0.95 (-0.69)		0.48	0.01	-0.01
C	17.78* (3.22)	-3.16* (-2.88)	-0.97 (-0.77)		4.42*	0.17	0.14

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

As for the piping trade, the result was similar to the regression of automation usage. There was not any model whose F value was significant at the 95% confidence level, which indicated the integration usage on the two factors was not observed to have significant impact on the piping unit rate productivity (Table 6.34).

Table 6.36: Regression of Latent Factors for Normalized Piping Unit Rate Productivity (Integration Use)

Model	Constant	Independent Variables			F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems				
A	0.35 (0.10)	0.81 (0.78)			0.60	0.03	-0.02
B	7.01 (1.97)		-1.27 (-1.13)		1.28	0.06	0.01
C	4.67 (0.82)	0.57 (0.53)	-1.12 (-0.95)		0.75	0.07	-0.02

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis.

The result for total trades was presented in Table 6.35 and Table 6.36. Model C included both latent factors and had the largest R^2 of 8% in the three models (Table 6.35). The F value of 6.85 was significant at the 95% confidence level and indicated the model's goodness of fit. The two latent factors' regression coefficients were also significant at the 95% confidence level, which indicated that the integration usage on both latent factors had significantly positive impact on all-trade unit rate productivity. Through the comparison of standardized regression coefficients, the integration usage on *Site Management Systems* had greater impact on all-trade unit rate productivity than the *Front End Planning and Engineering Systems* (Table 6.36).

Table 6.37: Regression of Latent Factors for Normalized All-trade Unit Rate Productivity (Integration Use)

Model	Constant	Independent Variables		F	R^2	Adjusted R^2
		Site Management Systems	Front End Planning and Engineering Systems			
A	7.39* (5.48)	-1.17* (-2.96)		8.78*	0.05	0.05
B	5.40* (3.99)		-0.65 (-1.47)	2.16	0.01	0.01
C	10.85* (5.22)	-1.34* (-3.37)	-0.94* (-2.18)	6.85*	0.08	0.07

Note: Dependent variable: normalized unit rate productivity; t-value shown in parenthesis; * denotes significance at the 0.05 level.

Table 6.38: Standardized Regression Coefficient for Model C in Table 6.35

Factor Scale	**Standardized Regression Coefficient**	**Average Factor Scale Score**	**Standard Deviation**
Site Management Systems	-0.27	3.28	0.40
Front End Planning and Engineering Systems	-0.17	2.98	0.43

6.5.3 Conclusions

Through the regression analyses, the author identified the impact of latent factors on construction unit rate productivity in regard to automation and integration usage. The result was consistent with the *t*-test in the previous section. The major findings are as follows:

1. In regard to the automation use, *Site Management Systems* was observed to have statistically significant impact on concrete, electrical and all-trade unit rate productivity; on structural steel unit rate productivity, the impacts of *Site Management Systems* and *Front End Planning and Engineering Systems* were similar and statistically significant.

2. In regard to the integration use, *Site Management Systems* was observed to have statistically significant impact on structural steel and electrical unit rate productivity. On concrete and all-trade unit rate productivity, both *Site Management Systems* and *Front End Planning and Engineering Systems* had statistically significant impact, while on concrete unit rate productivity, the second factor's impact was greater, and on all-trade unit rate productivity, the first factor's impact was greater.

3. On piping unit rate productivity, neither automation use nor integration use was found to have statistically significant impact.

6.6 Summary

In this chapter, the author examined the relationship of automation and integration to construction activity productivity through a series of *t*-test, and then identified the impact of latent factors in regard to automation and integration uses through factor analysis and regression analysis. The key findings in this chapter are summarized as follows:

1. The automation and integration use levels were lower on small projects than on large projects.
2. On small projects, only the automation of project information systems was related to better productivity.
3. On large projects, both the automation and integration of project information systems were related to better construction labor productivity performance, and the analyses suggested that a stronger relationship existed with integration;
4. On large projects, the effectiveness of automation and integration usage was observed to be different across the four trades. Automation usage was observed to be more positively related to structural steel and electrical productivity, while integration usage was observed to be more positively related to concrete and structural steel productivity. No significant positive relationship was observed in piping trade.
5. Two latent factors were identified from the 13 work functions: *Site Management Systems* and *Front End Planning and Engineering Systems.*
6. In regard to the automation use, *Site Management Systems* was observed to have significant positive impact on construction activity productivity; in regard to the integration use, both latent factors were observed to have significant positive impact on construction activity productivity, but the impact of *Site Management Systems* was greater.

CHAPTER 7 : CASE EXAMPLE

7.1 Introduction

The purpose of this chapter is to quantify the direct impact of an actual IT tool on construction productivity. A detailed examination of how Building Information Modeling (BIM), a current significant advancement of information technology usage on many construction projects, impacts the performance of a specific construction project is performed through this case example. The example project is the New UK Albert B. Chandler Hospital project. BIM is used in this project to detect design clashes and help drawing coordination. First, the author introduced the mechanics of how BIM was applied on this project and how it improved the automation and integration levels of clash detection process. Then through 10 clash detection/drawing coordination examples, the author performed a Benefit/Cost analysis to quantitatively present the direct impact of the BIM tool.

7.1.1 Project Description

The project design team is lead by GBBN with major sub consultants including AM Kinney, Ellerbe-Becket, Staggs and Fisher, Affiliated Engineers, THP Limited as well as a number of specialty consultants. The general contractor is Turner Construction. This project is constructing a new hospital addition to include patient beds, patient diagnostic and treatment areas, support areas, support facilities, medical equipment and infrastructure (Figure 7.1). The project also includes the replacement of the hospital parking garage and a connecting bridge to clear the site for the new hospital addition as well as land acquisition and utility relocation costs.

Figure 7.1: New UK Albert B. Chandler Hospital Project

The project fact sheet is as the following:

- 1.2 million square feet
- Five story (building has Ground level at grade, First, Second, Third, Fourth) podium plus a basement with two eight story patient bed towers on top
- 512 private patient rooms
- 28 operating rooms in the surgical suite
- Diagnostic Imaging includes two CT Scanners, two Digital Radiographic Rooms, one MRI.
- Wireless network and cell phone access throughout the building
- Opening in Spring 2011
- Emergency Room opening in Summer 2010
- Phase 1A - $532 million
- 1600 space parking structure
- 1.2 million square feet building with 550,000 square feet fit out (actual is 541,920 SF)

- Fit out space includes:
    - Pediatric and Adult Emergency Room
    - Two patient floors in the bed towers – 128 private rooms
    - Atrium
    - Chapel
    - Health Education Center
    - Auditorium
    - Surgery Waiting Room
    - One Heliport
    - Coffee Shop
- Architect of Record – GBBN Architects
- Health Care Design Architect – Ellerbe Becket

7.1.2 BIM Introduction

Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering and construction (AEC) industries. BIM is defined as the process of generating and managing building data during its life cycle (Lee et al, 2006). Typically it uses three-dimensional, real-time, dynamic building modeling software to increase productivity in building design and construction (Holness, 2008). The process produces the Building Information Model (also abbreviated BIM), which encompasses building geometry, spatial relationships, geographic information, and quantities and properties of building components. As more project information such as schedule and cost are incorporated in BIM, the model can be four-dimensional or five dimensional. The core value of BIM application is the great improvement on visualization, interoperability and integration.

Bentley and Autodesk are two major BIM product vendors in the United States. Both of the companies provide various BIM tools for the uses of design, construction and operation. MicroStation and ConstructSim are typical BIM tools for design and construction by Bentley, and Revit and Navisworks are their counterparts by Autodesk. Both companies also have specific tools for some trade contractors such as Bentley

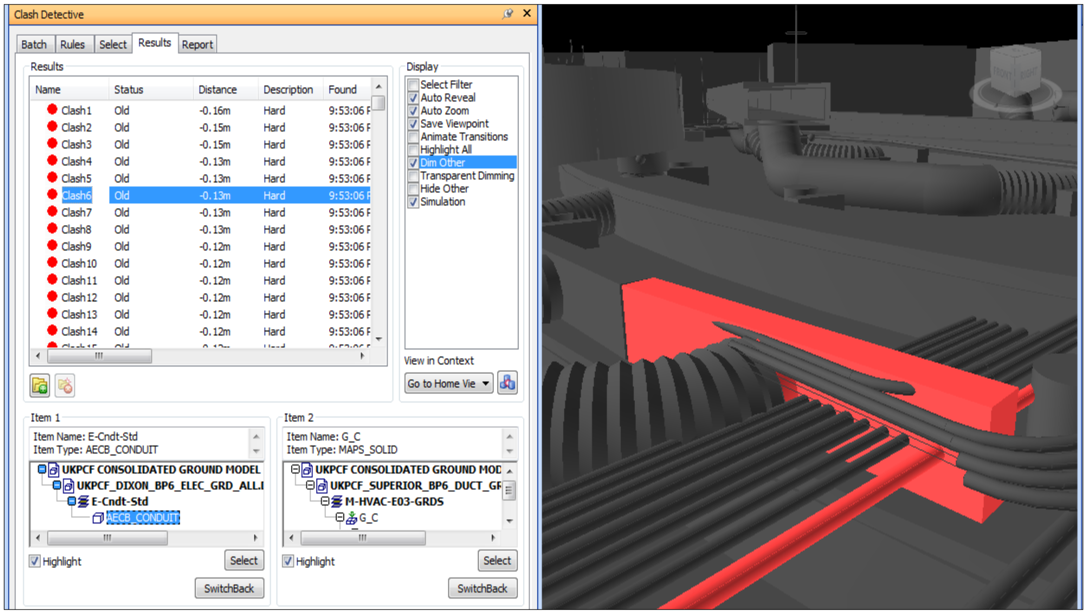
Building Mechanical Systems V8i and Autodesk® Revit® MEP (electrical engineering and plumbing design software).

Autodesk Navisworks Manage is the BIM tool used in this project for clash detection and drawing coordination among different parties, such as trade contractors and designers. The major features of Navisworks Manage are as follows (Autodesk, 2010):

- Model file and data aggregation - Combine project data into a single model for whole-project review.
- Real-time navigation - Examine the project model from every angle (Figure 7.2).
- Review toolkit - Review 3D projects regardless of file size or format.
- Collaboration toolkit - Facilitate easier project reviews.
- NWD and 3D DWF publishing- Publish the project to an easily distributed compressed file.
- 4D scheduling - Link model data to project schedules to plan project activities.
- Photorealistic visualization - Create realistic images and animations that improve understanding.
- Clash and interference detection - Find clashes and interferences before building begins (Figure 7.3).

Figure 7.2: NavisWorks Navigation Example

(Source: Autodesk.com, 2010)



Name	Status	Distance	Description	Found
● Clash1	Old	-0.16m	Hard	9:53:06 F
● Clash2	Old	-0.15m	Hard	9:53:06 F
● Clash3	Old	-0.15m	Hard	9:53:06 F
● Clash4	Old	-0.13m	Hard	9:53:06 F
● Clash5	Old	-0.13m	Hard	9:53:06 F
● Clash6	Old	-0.13m	Hard	9:53:06 F
● Clash7	Old	-0.13m	Hard	9:53:06 F
● Clash8	Old	-0.13m	Hard	9:53:06 F
● Clash9	Old	-0.12m	Hard	9:53:06 F
● Clash10	Old	-0.12m	Hard	9:53:06 F
● Clash11	Old	-0.12m	Hard	9:53:06 F
● Clash12	Old	-0.12m	Hard	9:53:06 F
● Clash13	Old	-0.12m	Hard	9:53:06 F
● Clash14	Old	-0.12m	Hard	9:53:06 F

☐ Select Filter
☑ Auto Reveal
☑ Auto Zoom
☑ Save Viewpoint
☐ Animate Transitions
☐ Highlight All
☑ Dim Other
☐ Transparent Dimming
☐ Hide Other
☑ Simulation

Item 1

Item Name: E-Cndt-Std
Item Type: AECB_CONDUIT

- UKPCF CONSOLIDATED GROUND MODEL
  - UKPCF_DIXON_BP6_ELEC_GRD_ALL.I
    - E-Cndt-Std
      - AECB_CONDUIT

☑ Highlight

Item 2

Item Name: G_C
Item Type: MAPS_SOLID

- UKPCF CONSOLIDATED GROUND MOD
  - UKPCF_SUPERIOR_BP6_DUCT_GF
    - M-HVAC-E03-GRDS
      - G_C

☑ Highlight

Figure 7.3: NavisWorks Clash Detective Example

7.2 Clash Detection and BIM Coordination Meeting

7.2.1 Clash Detection

A clash can be defined as the physical conflict between different systems or objects, such as between mechanical and electrical trades or two mechanical pipes. There are different types of clashes. In a hard clash, the two objects occupy the same place, in other words, one object intersects another one. In a soft clash or clearance clash, two objects are too close and there is insufficient space for access, insulation, safety, etc (Eastman et al, 2008). In a duplicate clash, the geometry of one object is the same as that of another object, located within a distance of between zero and the set tolerance.

Clashes can be resolved through coordination among different systems and trades. The conventional clash detection is to manually overlay individual system drawings on a light table and then identify potential conflicts by eyes. Today, most clash detection is still performed by this manual method (Eastman et al, 2008). A flow chart of the conventional clash detection method is shown as Figure 7.4. There are some limitation and disadvantage to identify clashes with light tables. First, all trade contractor must print their drawings in the same scale and same match lines; Second, the coordination meetings requires participants to be present in person which results in some travel and additional time and cost; Third, participants are likely to miss many clashes due to reviewing a three-dimension design with two-dimension drawings; Fourth, as more sheets are overlaid, there may not be sufficient light casting through the stack, which makes clash detection more difficult. Therefore, the common method is to lay 2 or 3 drawings on a light table at a time and exchange drawings until all necessary combination have been reviewed. Obviously, the traditional clash detection using a light table is very time-consuming and error prone.

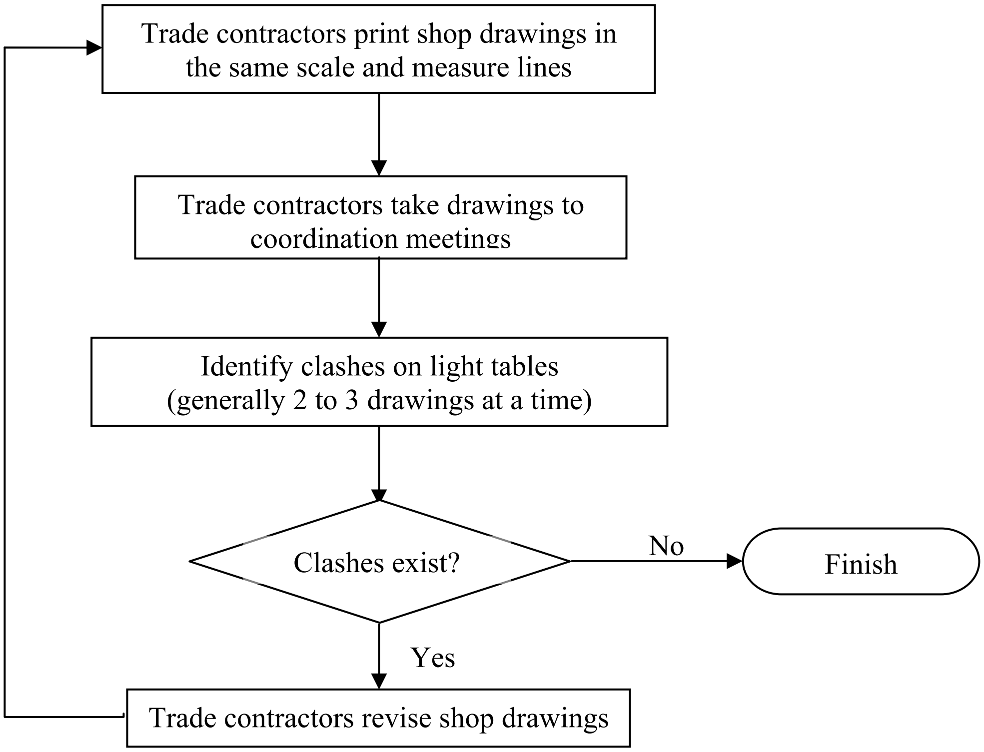
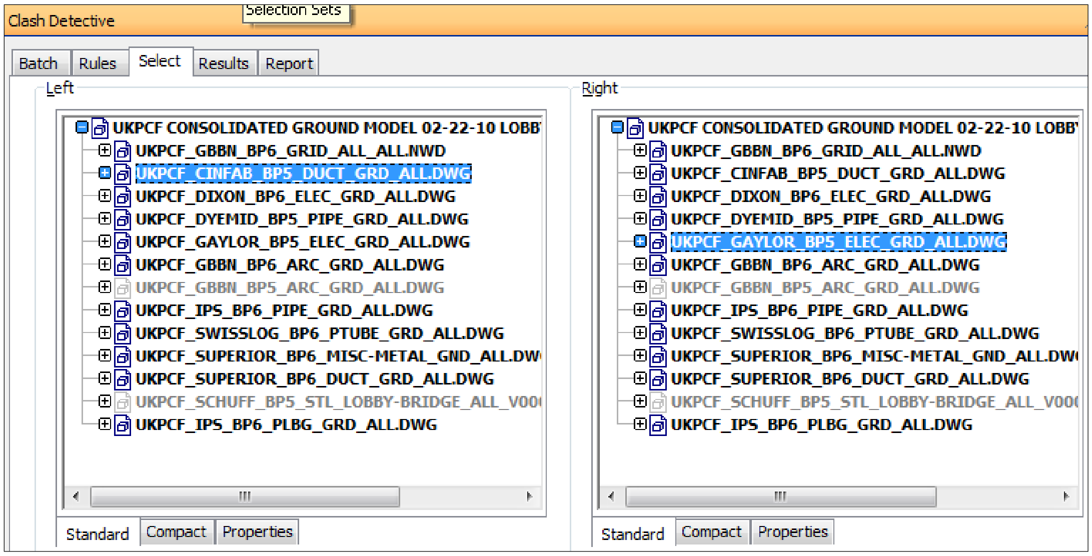


Figure 7.4: The Flow Chart of Conventional Clash Detection Using Light Tables

Fortunately, BIM tools such as NavisWorks provide many advantages over the conventional clash detection and drawing coordination. NavisWorks combines the automatic geometry-based clash detection and semantic and rule-based clash analysis. In addition, users have the freedom to run clash detective among any of two systems or trades through the selection tree (Figure 7.5). The detected clashes are grouped based on in which two systems the clashes happened (Figure 7.6). Users can also manage each of the clashes by approving it, or marking it active, reviewed or resolved through changing clash status (Figure 7.7). It is noted that not all "clashes" are real clashes such as the intersects of ceiling and lights (Figure 7.8). Users can approve these clashes or avoid reporting these clashes by setting up proper clash report rules.



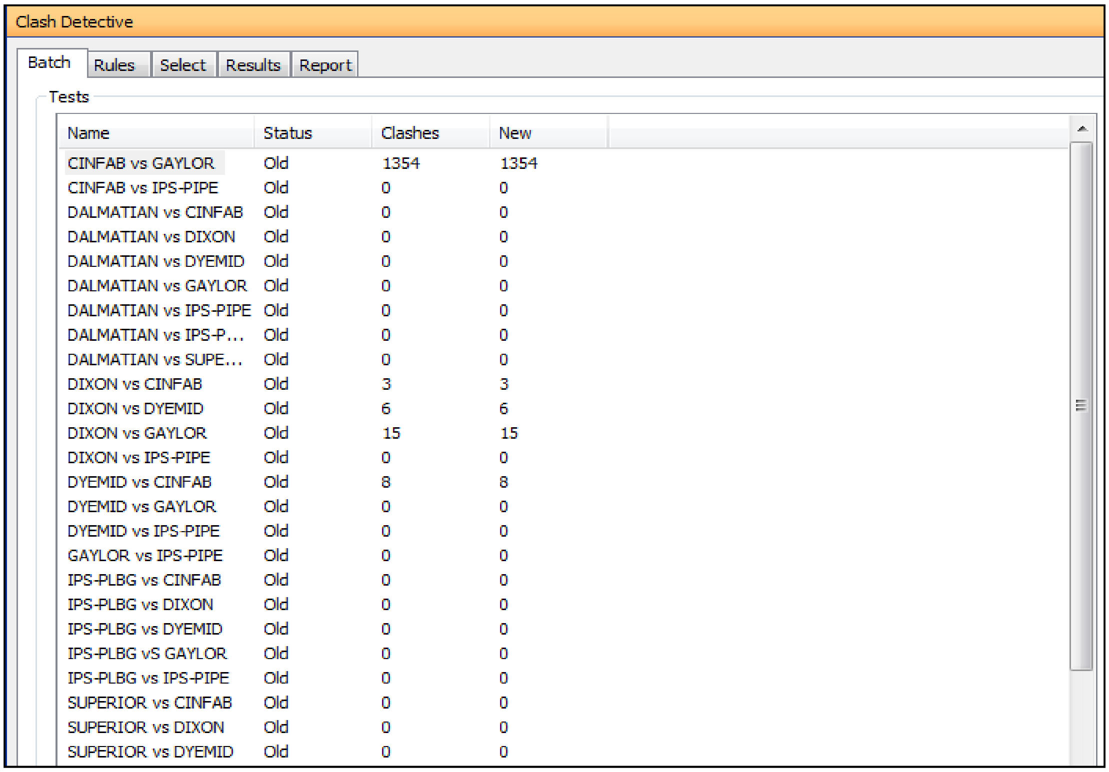
Left

- UKPCF CONSOLIDATED GROUND MODEL 02-22-10 LOBB
  - UKPCF_GBBN_BP6_GRID_ALL_ALL.NWD
  - UKPCF_CINFAB_BP5_DUCT_GRD_ALL.DWG
  - UKPCF_DIXON_BP6_ELEC_GRD_ALL.DWG
  - UKPCF_DYEMID_BP5_PIPE_GRD_ALL.DWG
  - UKPCF_GAYLOR_BP5_ELEC_GRD_ALL.DWG
  - UKPCF_GBBN_BP6_ARC_GRD_ALL.DWG
  - UKPCF_GBBN_BP5_ARC_GRD_ALL.DWG
  - UKPCF_IPS_BP6_PIPE_GRD_ALL.DWG
  - UKPCF_SWISSLOG_BP6_PTUBE_GRD_ALL.DWG
  - UKPCF_SUPERIOR_BP6_MISC-METAL_GND_ALL.DW
  - UKPCF_SUPERIOR_BP6_DUCT_GRD_ALL.DWG
  - UKPCF_SCHUFF_BP5_STL_LOBBY-BRIDGE_ALL_V00
  - UKPCF_IPS_BP6_PLBG_GRD_ALL.DWG

Right

- UKPCF CONSOLIDATED GROUND MODEL 02-22-10 LOBB
  - UKPCF_GBBN_BP6_GRID_ALL_ALL.NWD
  - UKPCF_CINFAB_BP5_DUCT_GRD_ALL.DWG
  - UKPCF_DIXON_BP6_ELEC_GRD_ALL.DWG
  - UKPCF_DYEMID_BP5_PIPE_GRD_ALL.DWG
  - UKPCF_GAYLOR_BP5_ELEC_GRD_ALL.DWG
  - UKPCF_GBBN_BP6_ARC_GRD_ALL.DWG
  - UKPCF_GBBN_BP5_ARC_GRD_ALL.DWG
  - UKPCF_IPS_BP6_PIPE_GRD_ALL.DWG
  - UKPCF_SWISSLOG_BP6_PTUBE_GRD_ALL.DWG
  - UKPCF_SUPERIOR_BP6_MISC-METAL_GND_ALL.DW
  - UKPCF_SUPERIOR_BP6_DUCT_GRD_ALL.DWG
  - UKPCF_SCHUFF_BP5_STL_LOBBY-BRIDGE_ALL_V00
  - UKPCF_IPS_BP6_PLBG_GRD_ALL.DWG

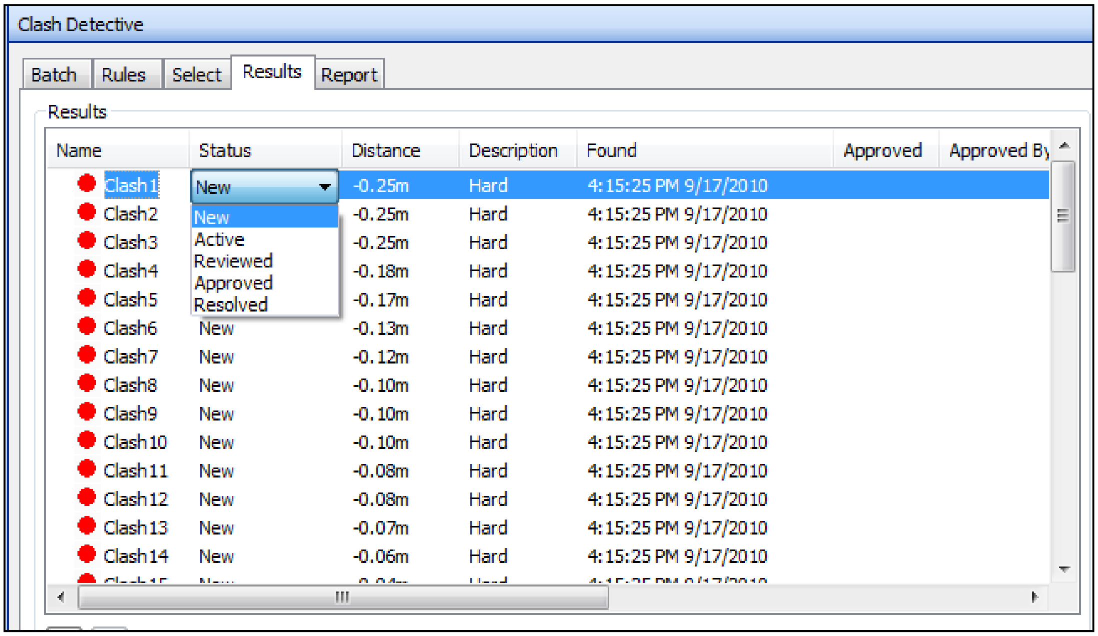
Figure 7.5: NavisWorks Clash Detective Selection Tree



Tests

Name	Status	Clashes	New
CINFAB vs GAYLOR	Old	1354	1354
CINFAB vs IPS-PIPE	Old	0	0
DALMATIAN vs CINFAB	Old	0	0
DALMATIAN vs DIXON	Old	0	0
DALMATIAN vs DYEMID	Old	0	0
DALMATIAN vs GAYLOR	Old	0	0
DALMATIAN vs IPS-PIPE	Old	0	0
DALMATIAN vs IPS-P...	Old	0	0
DALMATIAN vs SUPE...	Old	0	0
DIXON vs CINFAB	Old	3	3
DIXON vs DYEMID	Old	6	6
DIXON vs GAYLOR	Old	15	15
DIXON vs IPS-PIPE	Old	0	0
DYEMID vs CINFAB	Old	8	8
DYEMID vs GAYLOR	Old	0	0
DYEMID vs IPS-PIPE	Old	0	0
GAYLOR vs IPS-PIPE	Old	0	0
IPS-PLBG vs CINFAB	Old	0	0
IPS-PLBG vs DIXON	Old	0	0
IPS-PLBG vs DYEMID	Old	0	0
IPS-PLBG vS GAYLOR	Old	0	0
IPS-PLBG vs IPS-PIPE	Old	0	0
SUPERIOR vs CINFAB	Old	0	0
SUPERIOR vs DIXON	Old	0	0
SUPERIOR vs DYEMID	Old	0	0

Figure 7.6: NavisWorks Clash Detective Batch



Name	Status	Distance	Description	Found	Approved	Approved By
Clash1	New	-0.25m	Hard	4:15:25 PM 9/17/2010		
Clash2		-0.25m	Hard	4:15:25 PM 9/17/2010		
Clash3		-0.25m	Hard	4:15:25 PM 9/17/2010		
Clash4		-0.18m	Hard	4:15:25 PM 9/17/2010		
Clash5		-0.17m	Hard	4:15:25 PM 9/17/2010		
Clash6	New	-0.13m	Hard	4:15:25 PM 9/17/2010		
Clash7	New	-0.12m	Hard	4:15:25 PM 9/17/2010		
Clash8	New	-0.10m	Hard	4:15:25 PM 9/17/2010		
Clash9	New	-0.10m	Hard	4:15:25 PM 9/17/2010		
Clash10	New	-0.10m	Hard	4:15:25 PM 9/17/2010		
Clash11	New	-0.08m	Hard	4:15:25 PM 9/17/2010		
Clash12	New	-0.08m	Hard	4:15:25 PM 9/17/2010		
Clash13	New	-0.07m	Hard	4:15:25 PM 9/17/2010		
Clash14	New	-0.06m	Hard	4:15:25 PM 9/17/2010		

Figure 7.7: NavisWorks Clash Detective Result

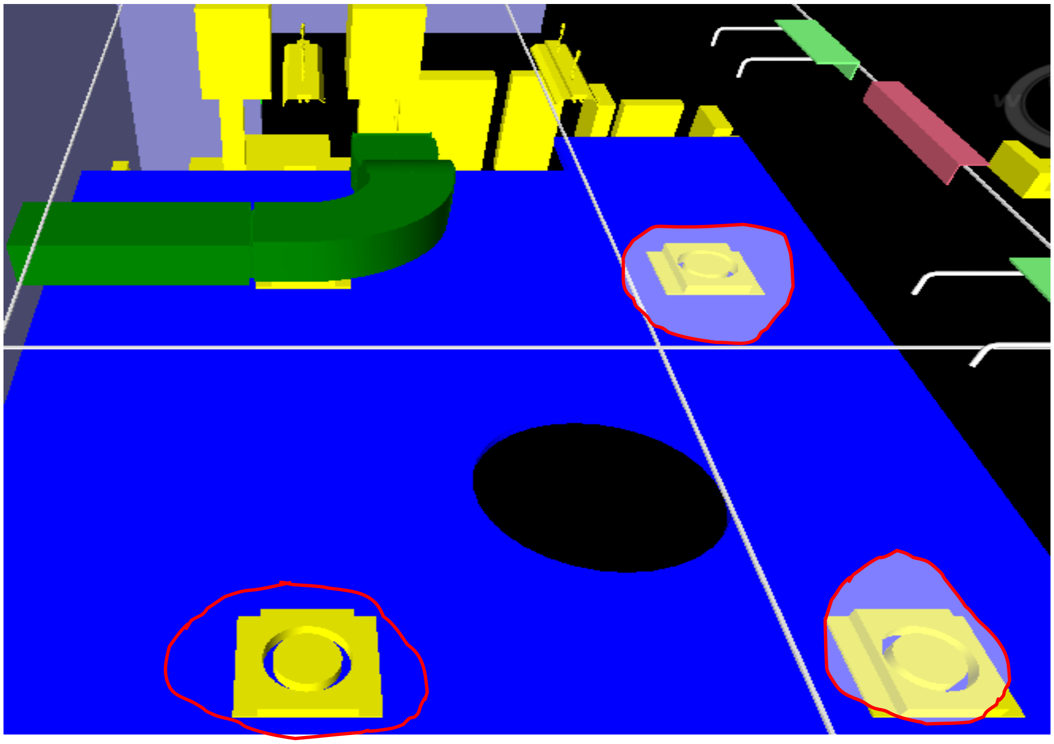


Figure 7.8: Example of False Clashes

7.2.1 BIM Coordination Meeting

In this project, clash resolutions are primarily worked out in BIM coordination meetings. Herein the author introduced the participants of the meetings, the necessary hardware and software and the coordination mechanics, i.e. how the meetings work.

Participants

The major participants of the BIM coordination meetings in this project are the general contractor and trade contractors. The general contractor needed to collect trade drawings (may be 2D CAD drawings or 3D Revit drawings), incorporate them to build a consolidated model (3D building information model) and then run the clash detective. According to the result, the general contractor identified which trade contractors were involved and then organized coordination meetings to meet with them. The architects didn't participate in BIM coordination meetings very often, because when clashes were detected between architects and trade contractors, the architects always had the first priority and trade contractors need to change their drawings. Occasionally, the owner attended meetings to advance their specific requirements or opinions.

Hardware and Software

Today, more meetings become webinars with various advanced IT tools. In this project, almost all of the BIM coordination meetings are webinars. Besides regular equipment like a telephone, a nice computer is necessary to run the NavisWorks. The system requirements are shown in Table 7.1.

Table 7.1: System Requirements for NavisWorks Manage 2011

Operating System	Windows XP or later versions
Web Browser	Microsoft® Internet Explorer 6.0, SP 1 or later for 32-bite; Internet Explorer 7.0 or later for 64-bite
Processor	AMD Athlon™ 3.0 GHz or faster (minimum); Intel® Pentium® 4, 3.0 GHz or faster (recommended) for 32-bite; AMD or Intel EM64T for 64-bite
RAM	2GB or greater (recommended)
Graphics card	128 MB, 1024 x 768 VGA, True Color (minimum); 256 MB or greater - 1280 x Graphics card 1024 32-bit color video display adapter, True Color (recommended)
Hard disk	Installation 1 GB

Source: Autodesk, 2010

Another important equipment is a SMART board (Figure 7.9). The SMART Board is an interactive whiteboard that uses touch detection for user input – e.g., scrolling, right mouse-click – in the same way normal PC input devices, such as a mouse or keyboard, detect input. A projector is used to display a computer's video output on the interactive whiteboard, which then acts as a large touch screen. The SMART Board typically comes with 4 digital pens, which use digital ink and replace traditional whiteboard markers.

Besides the regular software such as office suite, the required software include NavisWorks Manage from Autodesk ($9995 for the newest 2011 version) and web meeting software like GoToMeeting from Citrix Online, LLC ($468/year or $49/month). The companies or individuals hosting a meeting need to pay the cost, while anyone who joins the meetings can use GoToMeeting for free.

Since the official training information for NavisWorks Manage is not available in Autodesk, the author used the training time for Bentley's ConstructSim, which is comparable software of NavisWorks Manage, to estimate the training cost. The fundamental and intermediate course for ConstructSim requires 40 hours learning, so the training cost is $1434.8 for a civil engineer (based on median hourly rate of $35.87 from

BLS) or $1583.2 for a construction manager (based on median hourly rate of 39.58 from BLS).

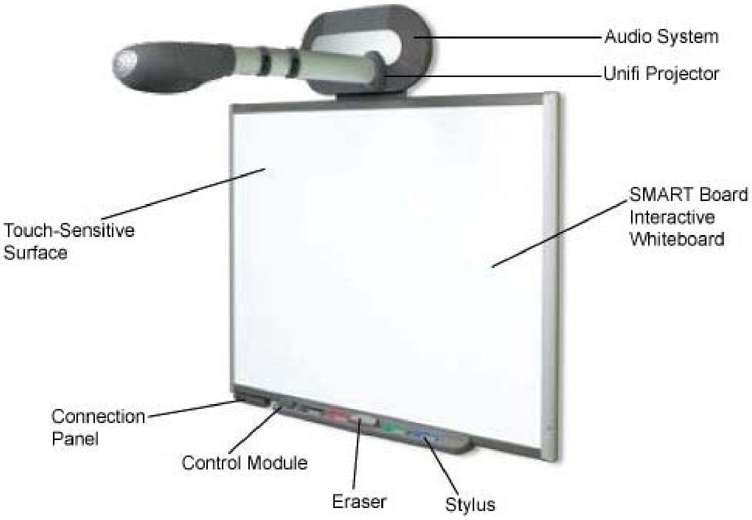


Figure 7.9: SMART Board

Coordination Meeting Mechanics

A flow chart of clash detection using BIM is shown as Figure 7.10. First, the general contractor set up a server to store and share BIM related files. The authorized users included architects, engineers and BIM coordinators from designers, general contractor and trade contractors. These users could upload/download files to/from this server. Primarily, four types of files are stored on the server:

- Designers' and trade contractors' drawings, which are often AutoCAD or Revit files. As a rule, each time after they update their drawings, they must use the updated one to replace the old one, rather than keep both on the server. This method keeps their drawings up-to-date and helps general contractor's BIM coordinator build models in NavisWorks with the latest drawings.
- Consolidated models, which were built by general contractor's BIM coordinator, consolidating the architect and trade contractors' drawings with NavisWorks. Different with the individual trade drawings, every consolidated model rather than the latest one is stored on the server. The date when the model was built must be

included in the file name, for example *2009-01-20 UKPCF CONSOLIDATED BASEMENT MODEL*.

- Sign off sheets, which are consolidated models' final version without any mistake.
- Meeting minutes, which are always PDF format files including screenshots in BIM coordination meetings.

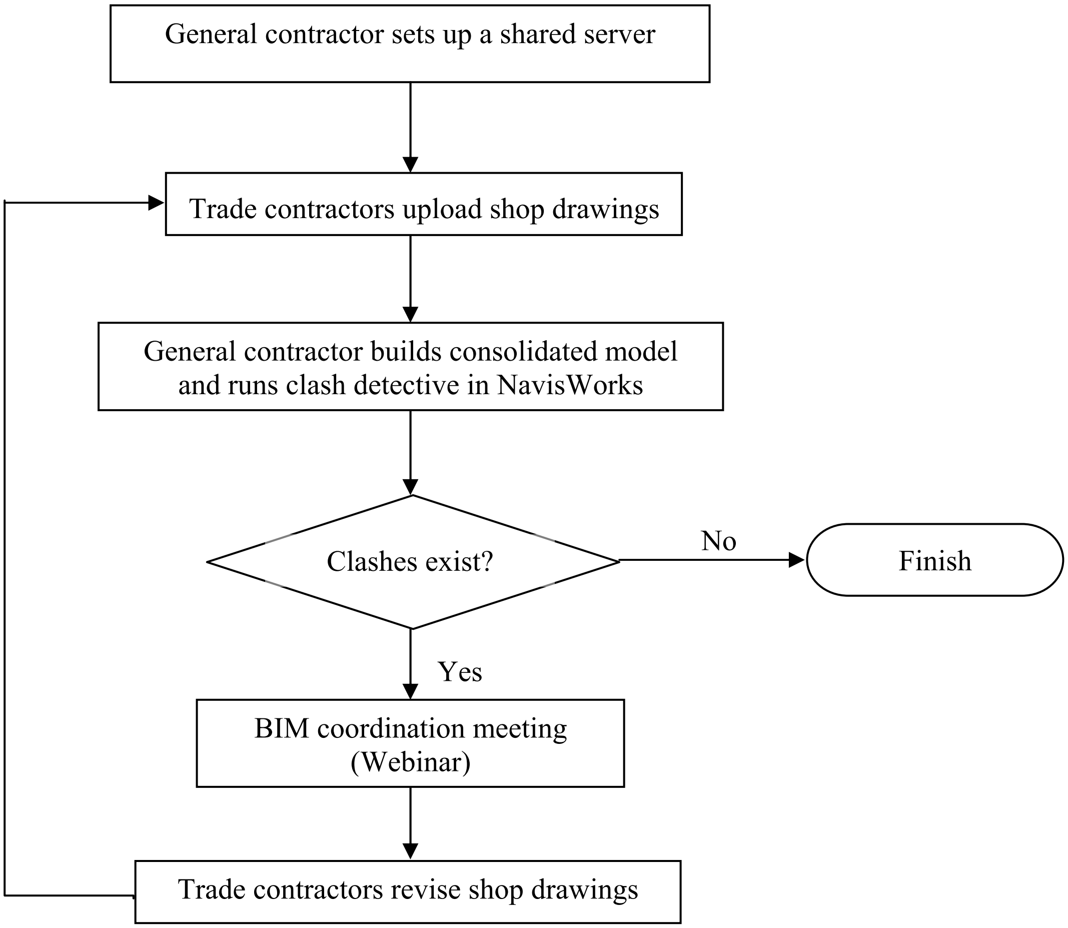


Figure 7.10: The Flow Chart of Advanced Clash Detection Using BIM

Before each coordination meeting, the general contractor is responsible for building a consolidated model and running the NavisWorks' clash detective. Any clash is saved as a viewpoint, which is the image of the place where the conflict happens (Figure 7.3). This function helps users conveniently save clash records and review them later. According to system priority and project schedule, the general contractor figures out which clashes are required to be resolved first, and then informs the involved parties to attend a BIM coordination meeting.

Participants can join the coordination meeting on site or online. Through GoToMeeting, the general contractor's BIM coordinator shares his computer screen with online participants to show the up-to-date model. At the same time, the model is also shown on the SMART board, which gives the on-site participants a clear view. Then participants review and discuss each of the clashes, and work out resolutions. To help identify where each clash is, NavisWorks can highlight conflicting components with red color and dim other parts as shown in Figure 7.3. The on-site participants can make any marks or comments on the SMART board (Figure 7.11). When a resolution is worked out, the screenshots can be saved into a PDF format file as meeting minutes. The notes in meeting minutes generally include who need to make change, what the changes are and by what scale. Sometimes, column numbers are also marked on the SMART board to help engineers find where the changes are (Figure 7.11).

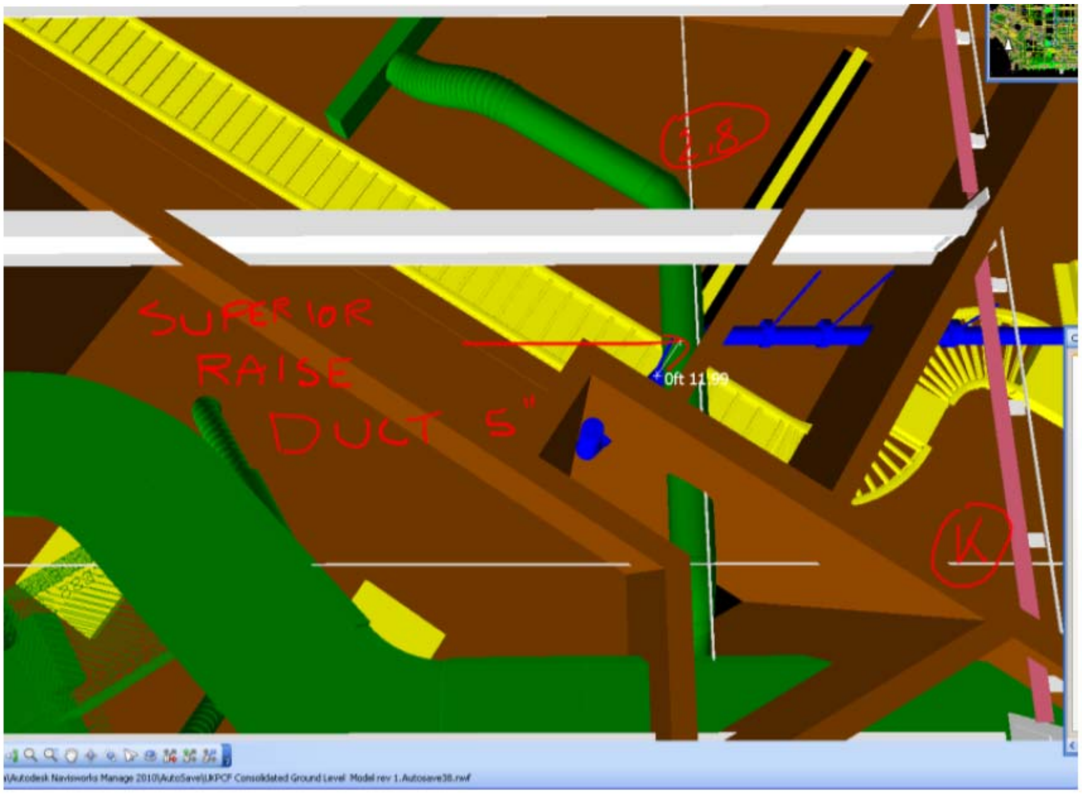


Figure 7.11: SMART Board Screenshot

If trade contractors' engineers also join the meeting, they can make changes immediately on their drawings. If they don't join the meeting, the meeting minutes are sent to them by email as instruction. Since the NavisWorks is a review tool rather than a design tool, the changes can only be made in AutoCAD or Revit. The trade contractors are required to update their drawings before next BIM coordination meeting, and upload them to the server, which allows general contractor's BIM coordinator to consolidate a new model before the next meeting. Since this project is very intense, generally there are two meetings on one day: the morning meeting often from 9AM-12PM, and the afternoon meeting from 2-5PM. After a new consolidated model is built, the general contractor needs to check if clashes or problems are resolved properly. If yes, the next meeting will begin to discuss new clashes.

7.3 Benefit/Cost Estimate

In this section, the author estimated the rework hours and cost for 10 clash examples assuming these clashes were not identified until construction and corresponding rework were required. The time spent on coordination meeting to work out solutions and drawing correction was also estimated. All of the ten clashes are selected from the hospital's ground level. The author selected these examples from five BIM coordinating meetings and the project's sever. There are three criteria to select the 10 examples: 1) There must be screen shots and meeting minutes for the examples to document the problems and solutions; 2) The examples or similar examples must be discussed in the five BIM coordination meetings that the author attended, which allowed the author to estimate the time spent on discussing the clashes and working out solutions; and 3) The construction activities of the examples must be included in the RS Means Manual, which allowed the author to perform the rework estimating. The author acknowledges that even though without BIM, these clashes may also be found through the conventional method with light tables. However, the traditional method cannot identify all clashes as quickly as NavisWorks and coordinate project parties as effectively as BIM coordination meetings.

Figure 7.12 shows a clash between a cable tray and a duct. The vertical yellow component is the cable tray that conflicts with a duct with green color on its right. The note shows that the trade contractor Dixon needs to fix this clash. It is very convenient to examine how the change is made in NavisWorks. The general contractor can just append Dixon’s new drawing to the old consolidated model. Then the model can show the cable tray in its old and new positions (Figure 7.13). In the red box of Figure 7.13, the yellow part shows the cable tray’s original position, and the green part shows its changed position.

Figure 7.12: Example 1 - A Clash between Cable Tray and Duct

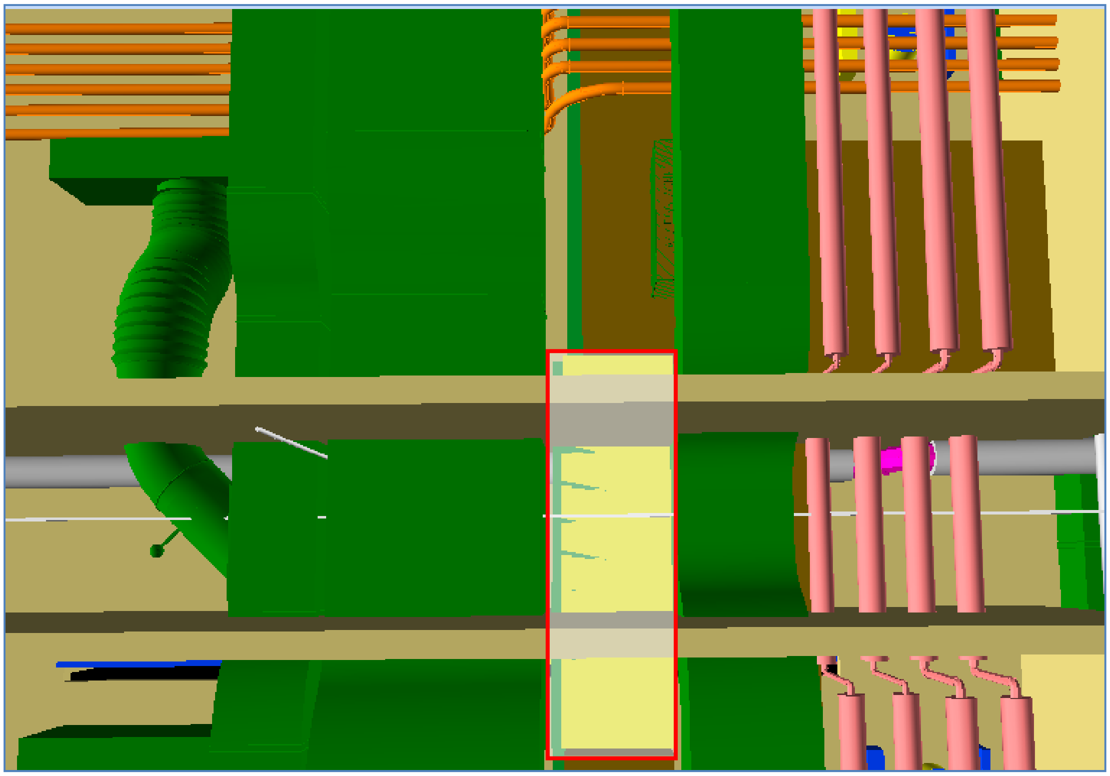


Figure 7.13: Showing the Same Component in Old and New Positions

In a complete building information model, each component's property information such as size and material should be incorporated. While in this project, the model was only used for the purpose of design examination and trade coordination, therefore, such property information was not included. The lack of building information limited the precision of the author's estimating. However, NavisWorks provides measure tools to help users measure distance or the size of any component (Figure 7.14). This tool helped the author perform estimating as precisely as possible. In addition, the author assumes the component is built with the most economical material available in RS Means Manual to make the estimating (i.e. the benefit of BIM) conservative. For this example, 6 feet of 18″×5″ cable tray needs to be moved left by 2 inches. If the clash was not identified, the rework would result in 1.2 work hours and $165.6 ($110.7 on material and $54.9 on labor, 2009 price). Through NavisWorks the clash was automatically identified, and it took the BIM coordinator and engineers approximately 10 minutes to discuss the problem and work out a solution, and the Dixion's engineer could make this change in AutoCAD drawing within 5 minutes (Table 7.2).

The other nine examples are presented in Figures 7.15 to 7.23, and the estimating is also shown in Table 7.2. The meeting time to work out a solution is estimated by the author based on the experience of sitting on this project's BIM coordination meetings. The time required to change drawings in AutoCAD is estimated by an architect who is proficient in AutoCAD. The author added additional three minutes to the architect's estimating for each case considering the time required to open AutoCAD and the drawings, and then find the place where changes are. Because three minutes are sufficient for the author to open a drawing in AutoCAD and find a specific place with column numbers, and trade contractors' engineers are more familiar with their drawings and more proficient in AutoCAD than the author, the time required to change drawings in Table 7.2 is a conservative estimate, although it seems very optimistic. It is noted that the actual material cost is less than the estimating because some materials can be reused in rework. The estimating result indicates that if the clashes were not found, the estimated rework would require 53.7 work hours and $2386 on labor and $2109.6 on materials assuming no materials are reused. While through BIM coordination meetings, the total meeting time plus drawing change time was just 2 hours and 44 minutes. From the aspect of time, the benefit to cost ratio is 19.6.

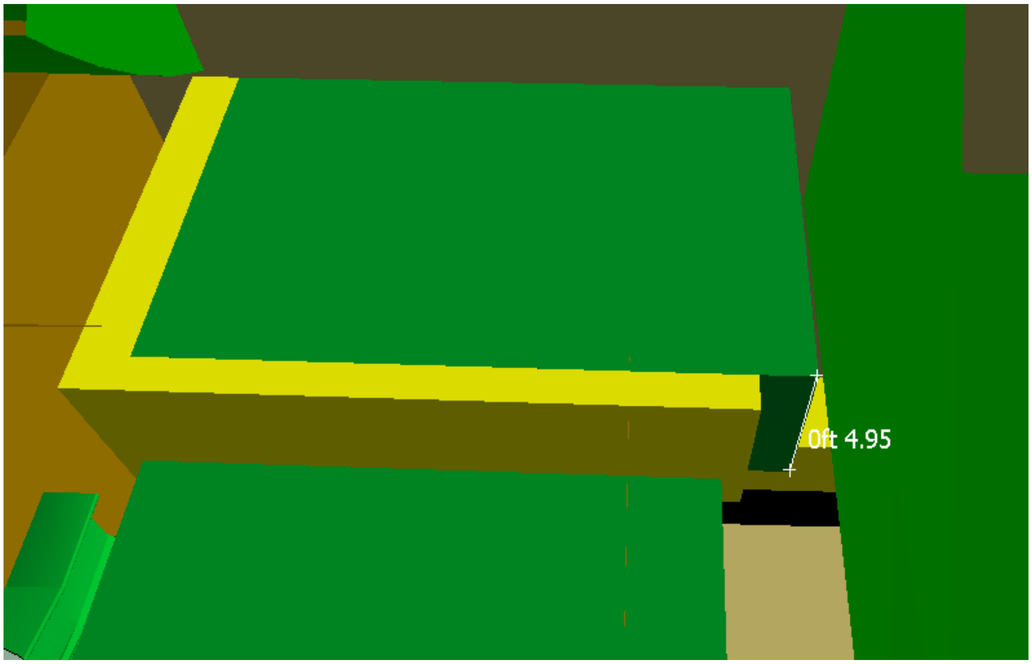


Figure 7.14: Component Measurement

Table 7.2: Comparison of Fixing Clashes on Site and through BIM

Example	Description		On Site Rework						BIM Coordination Meeting and Drawing Change Time	
			Unit	Quantity	Labor Hour	Material Cost ($)	Labor Cost ($)	Total Cost ($)	Meeting (Min)	Drawing Change (Min)
1	Offset able tray to clear duct		L.F.	6	1.2 (72)	110.7	54.9	165.6	10	5
2	Shift access door		Ea.	1	0.9 (54)	33.5	42	75.5	5	5
3	Raise duct to clear piping		L.F.	8	1.3 (78)	33.92	47.6	81.52	10	6
4	Correct downlight elevation		Ea.	1	0.8 (48)	22	37.5	59.5	15	7
5	Relocate vent piping off Terrace	Demolition	L.F.	61	3.2 (192)		158.6	158.6	20	6
		Installation	L.F.	27	7.2 (432)	240.3	315.9	556.2		
		Total	L.F.	88	10.4 (624)	240.3	474.5	714.8		
6	Raise distribution water pipes to clear duct		L.F.	80	20.0 (1200)	616	876	1492	10	5
7	Raise storm piping to clear duct		L.F.	36	12.8 (768)	687.6	561.6	1249.2	15	5
8	Raise duct to avoid piping		Lb	24	2.4 (144)	26.88	108	134.88	5	6
9	Shift downlight to avoid access door		Ea.	1	0.8 (48)	43.5	37.5	81	5	6
10	Reroute cable tray to avoid column		L.F.	16	3.1 (186)	295.2	146.4	441.6	10	8
Total					**53.7 (3222)**	**2109.6**	**2386.0**	**4495.6**	**105**	**59**
Benefit to Cost Ratio= 3222/ (105+59) = 19.6 (from the aspect of time)										

Note: The numbers in parentheses are labor time in minutes.

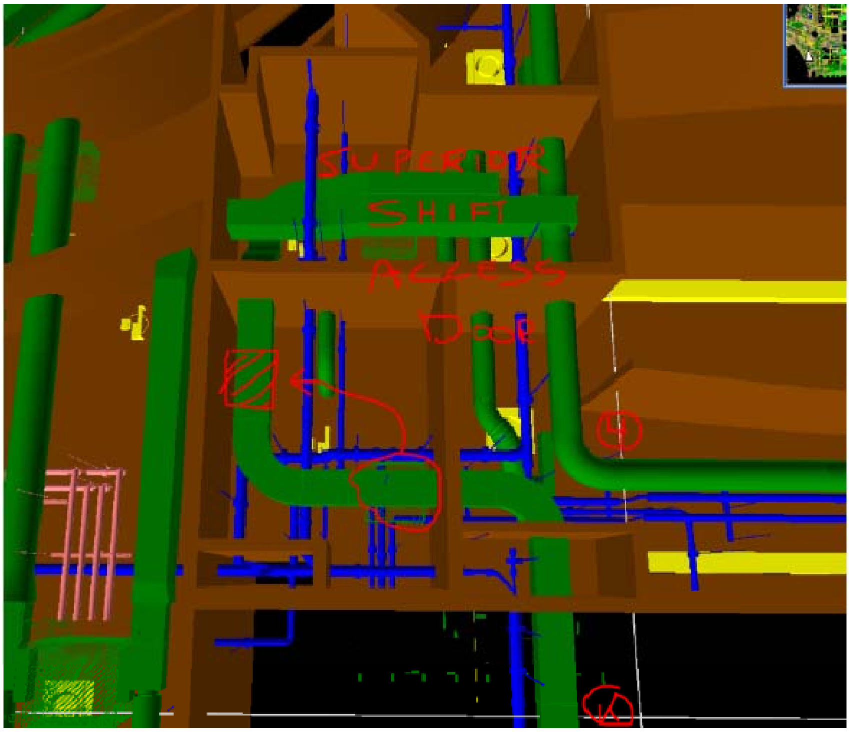


Figure 7.15: Example 2 – Shift Access Door to Avoid Piping

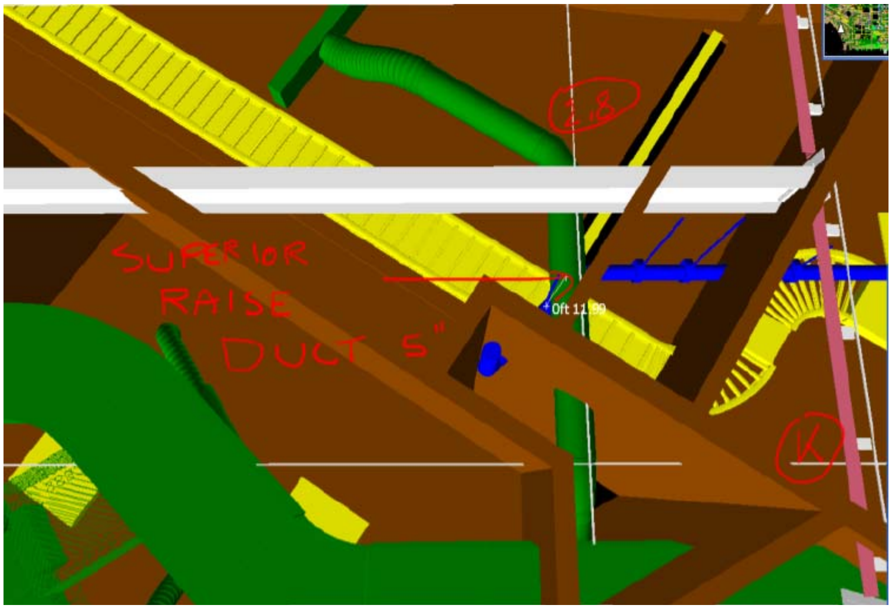


Figure 7.16: Example 3 – Raise Duct to Avoid Piping

Figure 7.17: Example 4 – Correct Light Elevation

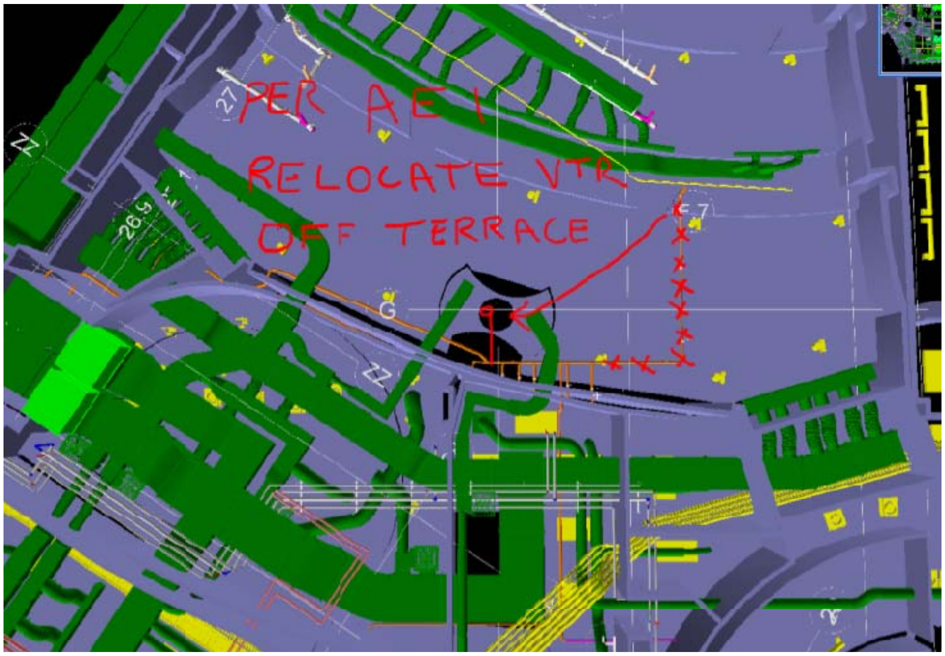


Figure 7.18: Example 5 – Relocate Vent Piping off Terrace

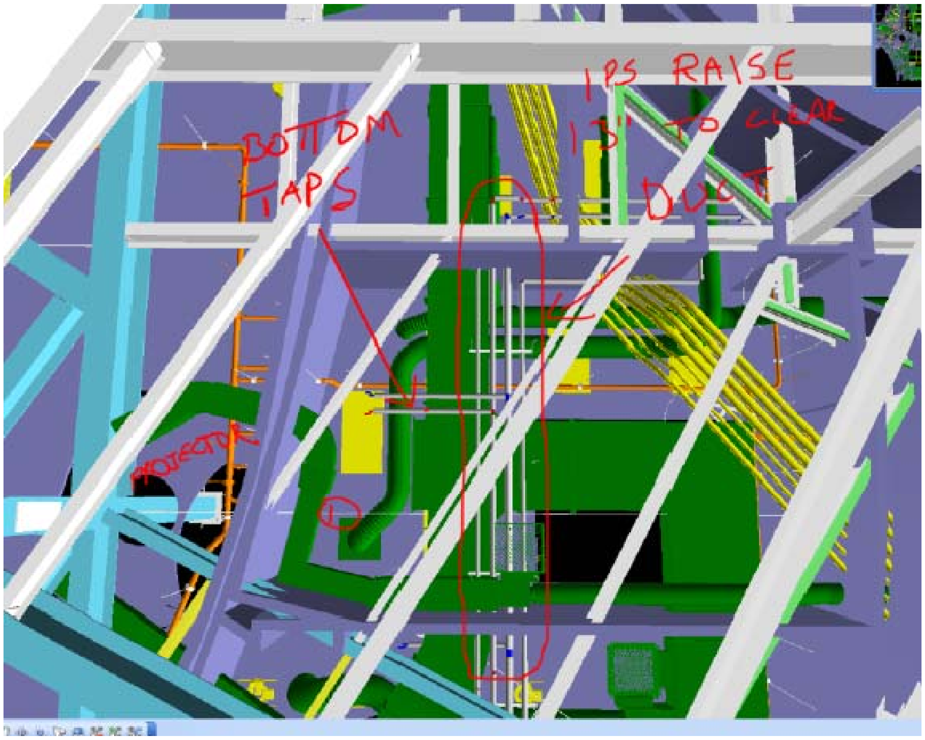


Figure 7.19: Example 6 – Raise Distribution Water Pipes to Clear Duct

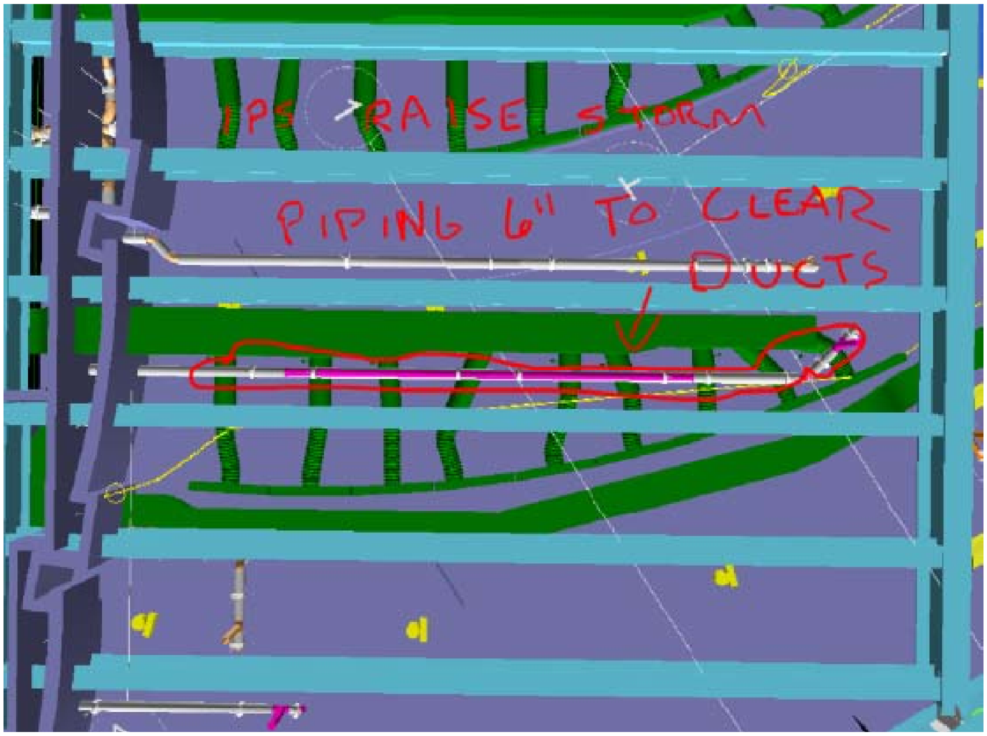


Figure 7.20: Example 7 – Raise Storm Piping to Clear Ducts

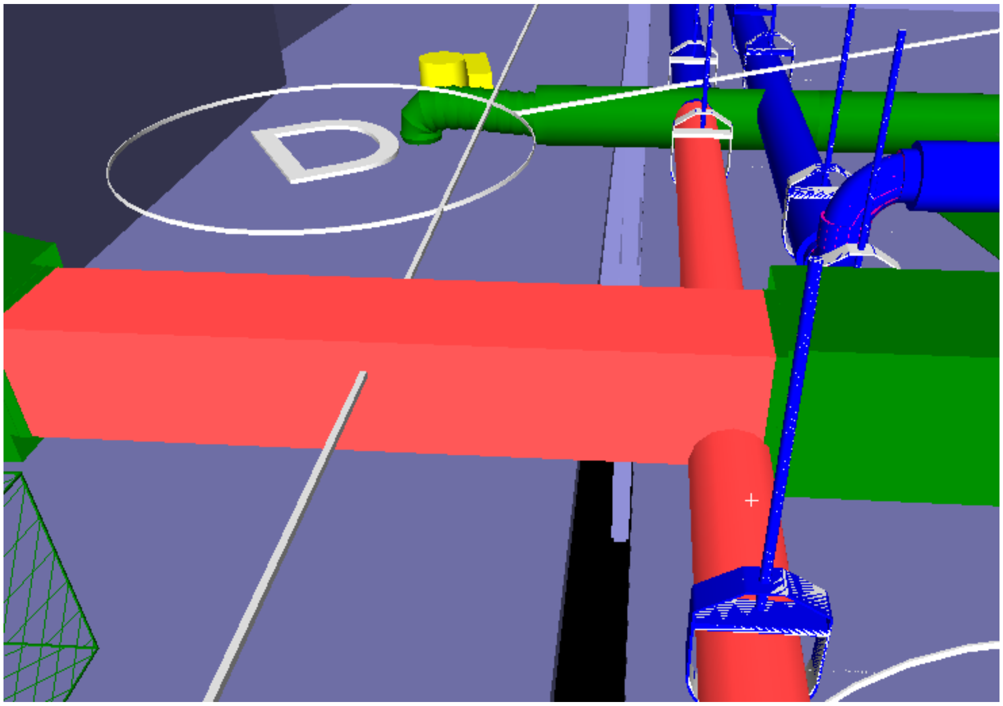


Figure 7.21: Example 8 – Raise Duct to Avoid Piping

Figure 7.22: Example 9 – Shift Light to Avoid Access Door

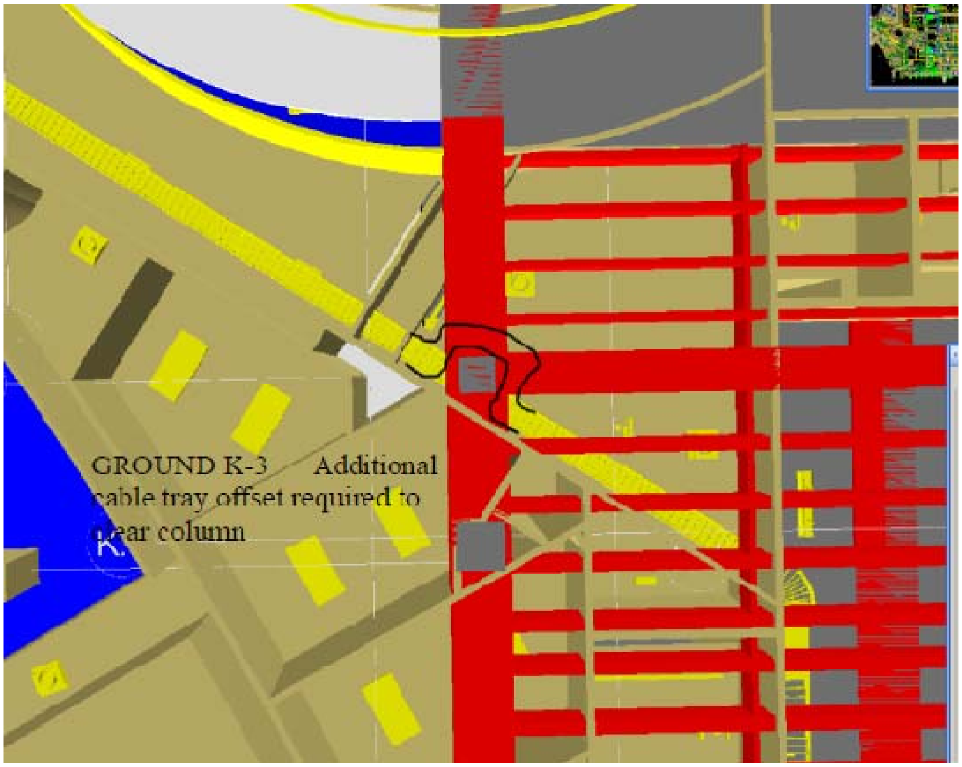


Figure 7.23: Example 10 – Reroute Cable Tray to Clear Column

To further present how BIM effectively benefited clash detection and drawing coordination, Table 7.3 shows the clash summary of the first consolidated ground level model, which was built with the trade contractors' original ground level drawings. All of the 1861 clashes were resolved within 50 days. Table 7.3 also indicates the most clashes occurred between the piping and electrical trades. The result is not unexpected, and the reasons are as follows: (1) there are multiple trade contractors involved in the two trades (two in electrical and three in piping trades); (2) the electrical and piping systems are more complex than other systems like steel or concrete, and their positions are often very close.

Table 7.3: Clash Summary of the First Consolidated Ground Model

Trade	Duct	Electrical	Piping	Steel
Duct	-	71	36	69
Electrical	(71)	15	1117	40
Piping	(36)	(1117)	289	224
Steel	(69)	(40)	(224)	-

Note: blank cells no clash detection run between the two trades;
the numbers in parentheses are duplicate result.

The direct rework cost of $4495.6 and 53.7 rework hours seem not to be very significant for a 500 million dollars project, but considering the 10 clash examples were just a very small part of the total clashes in this project, the savings on rework would be numerous. In addition, if the clashes could not be identified until construction, besides the rework they would also lead to other serious issues such as schedule slippage, disputes among project partners and many change orders. The indirect loss from these issues could be much larger than the direct rework cost and time.

7.3 Summary

With the function of automated clash detection, BIM software such as NavisWorks obviously involves automation technology. With the ability to consolidate shop drawings from various trade contractors and architects, it also involves advanced information integration technology. The server used to store and share project document, the SMART Board used to make notes and meeting minutes as well as the webinar software used to organize coordination meetings also improved the levels of automation and integration on this project. In Chapter 6, 13 work functions were identified on a typical capital project. For this project, at least two work functions' automation and integration levels were improved because of BIM and the tools mentioned above: coordination systems and communication systems. Since most clashes were found between/within piping and electrical trades, and the advanced clash detection method with BIM could help avoid all rework due to design clashes, it is reasonable to conclude the construction productivity of the two trades would be improved. This result is consistent with the statistical analyses in Chapter 6. As shown in Tables 6.6, automation on coordination systems and communication systems were found to have strong and moderate positive relationship with electrical productivity. As shown in Table 6.7, integration on coordination systems and communication systems were found to have moderate and strong positive relationship with electrical productivity. This chapter is also a supplement to Chapter 6. In Chapter 6, no significant relationship were observed between automation and integration usage and piping productivity, while in this case example, improved automation and integration on coordination systems and communications systems obviously benefited the piping trade.

Finally, the benefit and advantage of clash detection with BIM are summarized as follows:

- The 3D model increased the visualization of the drawing review. The reviewers can get an easy and straightforward view of the actual building and they don't have to transform the 2D drawings to 3D image with their own imagination.
- The digital model and computer-based review eliminated the time and cost on printing.
- The roaming function in NavisWorks allows reviewers to examine the design from all aspects and thus helps them make accurate evaluation and solutions.
- The automatic clash detective function of NavisWorks makes drawing coordination process quick, easy and free of omission. This is the primary advantage of NavisWorks, which significantly shortens the time spent on drawing coordination compared with the traditional method.
- The shared server and uniform rules of document storage strengthened information integration, and eliminated waiting time and any error in document delivery or transfer.
- GoToMeeting allowed meeting organizers to share their computer screen conveniently, and any marks and notes on SMART board could be seen by all participants. This made the webinar almost the same as face-to-face meeting. Sufficient communication reduced travel cost, accelerated the work pace and improved productivity.
- The effective clash detection significantly reduced rework and change order. As evidence, there was no rework in this project due to the design conflict and the

constructed systems were well coordinated (Figure 7.22) just as what they were shown in the model (Figure 7.23). Without BIM, this result cannot be imagined.

- From the aspect of time, the benefit to cost ratio is 19.6.

Figure 7.24: Good Coordination among Plumbing, HVAC and Concrete (Actual)

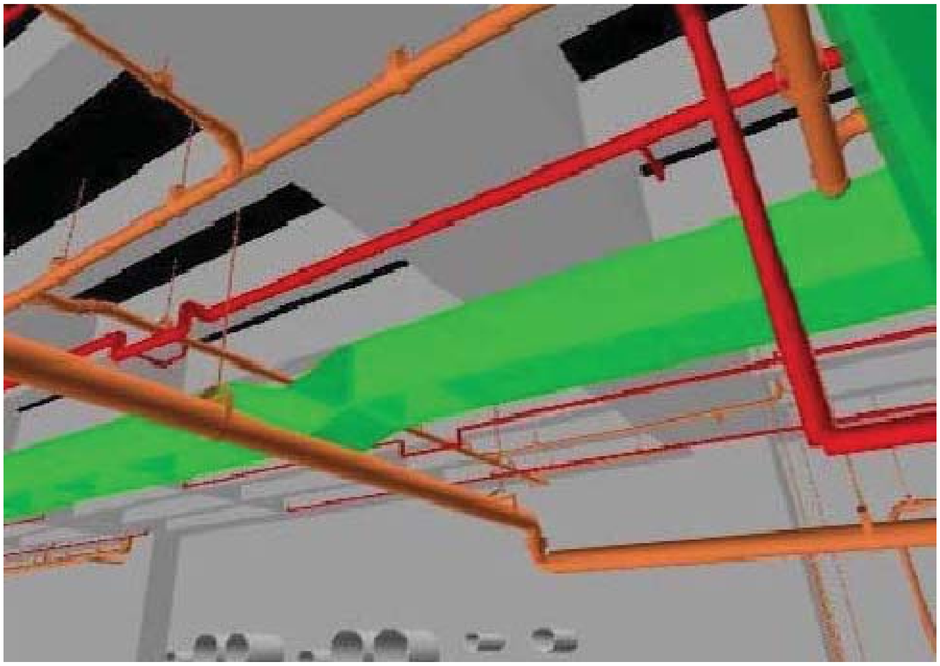


Figure 7.25: Good Coordination among Plumbing, HVAC and Concrete (Model)

CHAPTER 8 : CONCLUSIONS AND RECOMMENDATIONS

8.1 Main Conclusions

Based on the research's findings, the following conclusions are presented:

1. A simple positive relationship of construction productivity to information and national communication technology (ICT) investment can be observed in the study's national-level data from OECD and GGDC although a few countries such as Austria are exceptions. The gap between construction productivity improvement and national information technology investment existed, which was 12 years for most of the sampled countries in this research. It is noted that this gap is not applicable for a specific construction company or project.
2. From 1980 to 2005, the construction industry's ranking was low in the total U.S industries, by labor productivity improvement and ICT capital contribution to value added growth. But the ranking has increased in the long term.
3. A statistically positive relationship can be observed between ICT capital contribution and labor productivity improvement in the U.S total industries, i.e. the industries with higher ICT contribution experienced greater labor productivity improvement than those with lower ICT contribution. A gap about 10 years was observed between the ICT contribution and labor productivity improvement. This gap is at the industrial level and also not applicable to any specific company.
4. On large capital projects, both the automation and integration of project information systems were related to better construction labor productivity performance, and a stronger relationship existed with integration. The effectiveness of automation and integration usage was observed to be different across different trades.
5. In regard to the automation use, two latent factors were identified from the 13 work functions: *Site Management Systems* and *Front End Planning and Engineering Systems*. The first factor was observed to have significant positive impact on construction activity productivity.
6. In regard to the integration use, also the two latent factors were identified from the 13 work functions: *Site Management Systems* and *Front End Planning and*

Engineering Systems. Both latent factors were observed to have significant positive impact on construction activity productivity, but the impact of *Site Management Systems* was greater.

8.2 Research Contributions

This research contributes to the construction research as follows:

1. This is the first comprehensive research, based on the researcher's knowledge, to investigate the general relationship between construction productivity and information technology.
2. This research documented the trend of international construction productivity and identified the relationship of national construction productivity and national information and communication technology investment.
3. This research identified the impact of automation and integration of information systems of construction projects and revealed the difference across different trades and work functions.
4. This research provided theoretical and practical evidence to construction companies in regards to the benefit of information technology on construction productivity.

8.3 Limitation of the Research

In the national-level and industry-level analyses, the construction productivity was based on the aggregate output measurement. Therefore, it was also subject to the problem of the accuracy of construction productivity as many other related research efforts have also experienced.

In the project level analysis, this research focused on the industrial projects and several specific trades due to the support from the Construction Industry Institute, which limited the application of the research finding in other sectors like residential construction and other trades like mechanical.

8.4 Recommendations for Further Research

Based on the findings and limitations of this research in regards to the relationship between construction productivity and information technology, it recommends the following for future research;

1. The development of reliable input and output indices for construction industry is necessary as well as an aggregate or macro-level construction productivity measurement. This should be a joint effort of construction researchers and economists.
2. There is a need to collect and analyze more data and indicators in regards to the information technology application and development in the construction industry.
3. There is a need to extend this research to other types of construction projects, such as infrastructure and building projects.
4. It is important to examine the relationship of construction factor productivity to information technology. A labor productivity analysis is more straightforward, since its impact is restricted to just the labor component of productivity, but factor productivity represents the ratio of output to all inputs including labor, equipment and materials. Positive results with factor productivity are likely to produce more compelling arguments for construction to adopt new automation and integration technologies.

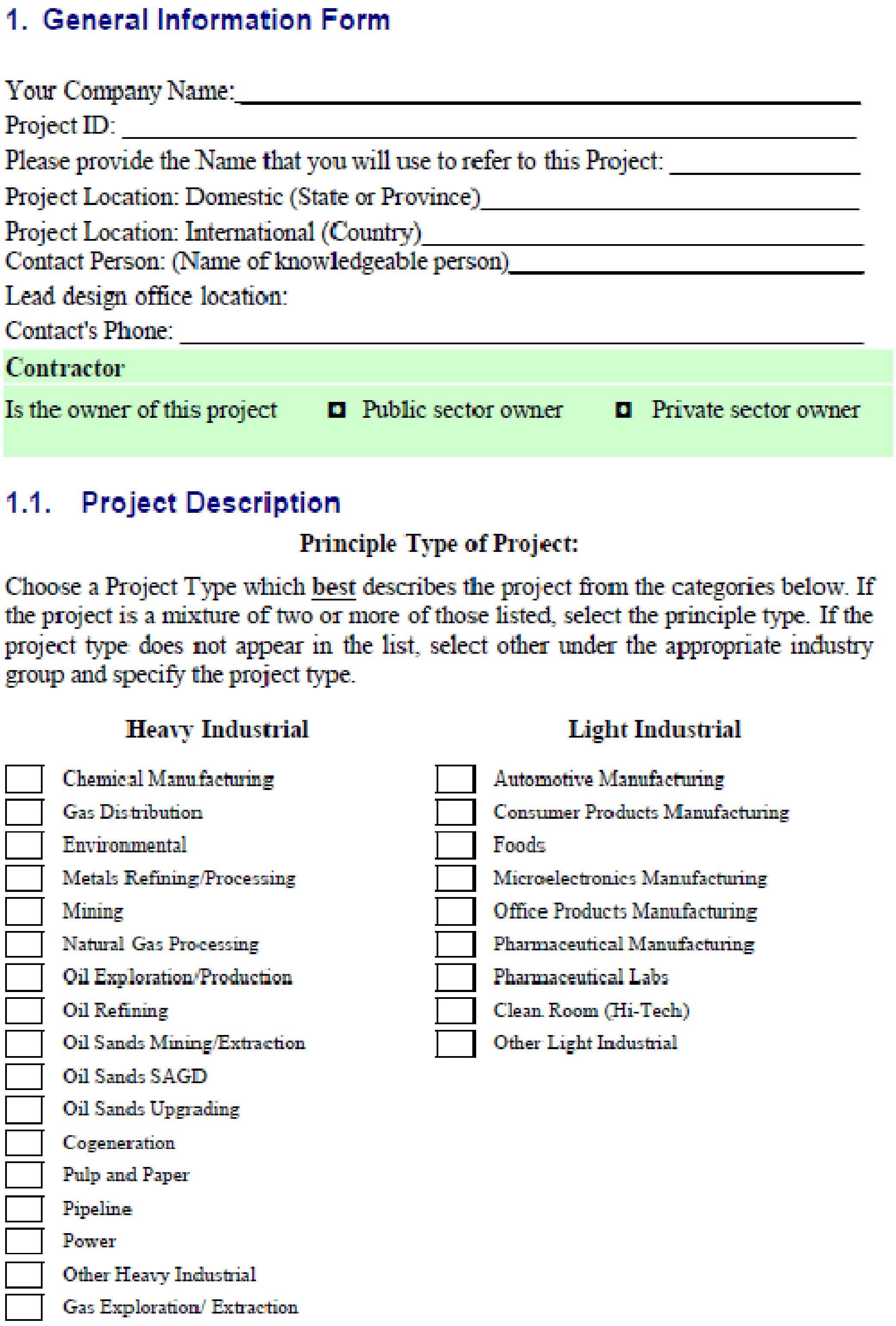
8.5 Recommendations for Future Industry Action

Although the US construction industry has traditionally been considered technically stagnant, this research found the contribution of information technology to the construction industry has been increasing in the long run. Therefore, there are some recommendations for construction companies for the sake of improving their productivity:

1. It is important for construction companies to have more access to construction research in regards to available innovations and applications of information technology.
2. There is no doubt that construction companies needs to improve the automation and integration of their information systems. However, when to adopt an

innovation and to what extent are the logical next questions. Therefore, it will be very helpful to have a robust tool or process that can assess the likelihood of whether a proposed information technology would help improve construction productivity and what the expected impact is. This should be a joint effort of the construction industry and the academia.

APENDIX A: CII BENCHMARKING AND MATRIX PROGRAM SURVEY FOR LARGE PROJECTS (PARTS)



1. General Information Form

Your Company Name: ________________________

Project ID: ________________________

Please provide the Name that you will use to refer to this Project: ____________

Project Location: Domestic (State or Province)________________

Project Location: International (Country)________________

Contact Person: (Name of knowledgeable person)________________

Lead design office location:

Contact's Phone: ________________________

Contractor

Is the owner of this project ☐ Public sector owner ☐ Private sector owner

1.1. Project Description

Principle Type of Project:

Choose a Project Type which best describes the project from the categories below. If the project is a mixture of two or more of those listed, select the principle type. If the project type does not appear in the list, select other under the appropriate industry group and specify the project type.

Heavy Industrial

- ☐ Chemical Manufacturing
- ☐ Gas Distribution
- ☐ Environmental
- ☐ Metals Refining/Processing
- ☐ Mining
- ☐ Natural Gas Processing
- ☐ Oil Exploration/Production
- ☐ Oil Refining
- ☐ Oil Sands Mining/Extraction
- ☐ Oil Sands SAGD
- ☐ Oil Sands Upgrading
- ☐ Cogeneration
- ☐ Pulp and Paper
- ☐ Pipeline
- ☐ Power
- ☐ Other Heavy Industrial
- ☐ Gas Exploration/ Extraction

Light Industrial

- ☐ Automotive Manufacturing
- ☐ Consumer Products Manufacturing
- ☐ Foods
- ☐ Microelectronics Manufacturing
- ☐ Office Products Manufacturing
- ☐ Pharmaceutical Manufacturing
- ☐ Pharmaceutical Labs
- ☐ Clean Room (Hi-Tech)
- ☐ Other Light Industrial

Buildings

☐ Communications Center
☐ Courthouse
☐ Dormitory/Hotel/Housing/Residential
☐ Embassy
☐ Low rise Office (<3 floors)
☐ High rise Office (>3 floors)
☐ Hospital
☐ Laboratory
☐ Maintenance Facilities
☐ Movie Theatre
☐ Parking Garage
☐ Physical Fitness Center
☐ Prison
☐ Restaurant/Nightclub
☐ Retail Building
☐ School
☐ Warehouse
☐ Other Buildings

Infrastructure

☐ Airport
☐ Electrical Distribution
☐ Flood Control
☐ Highway
☐ Marine Facilities
☐ Navigation
☐ Rail
☐ Tunneling
☐ Water/Wastewater
☐ Telecom, Wide Area Network
☐ Other Infrastructure

If other, please describe: ______________________________

1.2. Project Nature

From the list below select the category that best describes the nature of this project. If your project is a combination of these natures, select the category that you would like your project to be benchmarked against. Please see the glossary for definitions.

The Project Nature was:
☐ Grass Roots, Greenfield
☐ Modernization, Renovation, Upgrade
☐ Addition, Expansion
☐ Other Project Nature (Please describe):____________

3.11. Automation/Integration (AI) Technology

This section addresses ***the degree of automation/level of use and integration of automated systems*** for specific tasks/work functions common to most projects. Using the first matrix, please assess the degree of automation and level of use ***only***. Using the second matrix, please assess the level of integration of these automated systems among the tasks/work functions.

Referring to the use levels below, indicate how well for this project, the tasks/work functions were automated. Select the single most appropriate ***use level*** for the task/work functions listed.

USE LEVELS

- **Level 1(None/Minimal):** Little or no utilization beyond e-mail.
- **Level 2 (Some):** "Office" equivalent software, 2D CAD for detailed design.
- **Level 3 (Moderate):** Standalone electronic/automated engineering discipline (3D CAD) and project services systems.
- **Level 4 (Nearly Full):** Some automated input/output from multiple databases with automated engineering discipline design and project services systems.
- **Level 5 (Full):** Fully or nearly fully automated systems dominate execution of all work functions.

Automation of Task/Work Functions

	Use Level						
Task/Work Functions	1	2	3	4	5	NA	UNK
Business planning and analysis	☐	☐	☐	☐	☐	☐	☐
Conceptual definition & design	☐	☐	☐	☐	☐	☐	☐
Project (discipline) definition & facility design	☐	☐	☐	☐	☐	☐	☐
Supply management	☐	☐	☐	☐	☐	☐	☐
Project management							
Coordination system	☐	☐	☐	☐	☐	☐	☐
Communications system	☐	☐	☐	☐	☐	☐	☐
Cost system	☐	☐	☐	☐	☐	☐	☐
Schedule system	☐	☐	☐	☐	☐	☐	☐
Quality system	☐	☐	☐	☐	☐	☐	☐
Off-site/pre-construction	☐	☐	☐	☐	☐	☐	☐
Construction	☐	☐	☐	☐	☐	☐	☐
As-built documentation	☐	☐	☐	☐	☐	☐	☐
Facility start-up & life cycle support	☐	☐	☐	☐	☐	☐	☐

Referring to the integration levels below, indicate how well for this project, the tasks/work functions were ***integrated across all other*** work functions. Select the single most appropriate ***integration level*** for the task/work functions listed.

INTEGRATION LEVELS

- **Level 1(None/Minimal):** Little or no integration of electronic systems/applications.
- **Level 2 (Some):** Manual transfer of information via hardcopy of email.
- **Level 3 (Moderate):** Manual and some electronic transfer between automated systems.
- **Level 4 (Nearly Full):** Most systems are integrated with significant human intervention for tracking inputs/outputs.
- **Level 5 (Full):** All information is stored on a network system accessible to all automation systems and users. All routine communications are automated. The automated process and discipline design systems are fully integrated into 3D design, supply management, and project services systems (cost, schedule, quality, and safety).

Integration of Task/Work Functions

	Integration Level						
Task/Work Functions	1	2	3	4	5	NA	UNK
Business planning & analysis	☐	☐	☐	☐	☐	☐	☐
Conceptual definition & design	☐	☐	☐	☐	☐	☐	☐
Project (discipline) definition & facility design	☐	☐	☐	☐	☐	☐	☐
Supply management	☐	☐	☐	☐	☐	☐	☐
Project management							
Coordination system	☐	☐	☐	☐	☐	☐	☐
Communications system	☐	☐	☐	☐	☐	☐	☐
Cost system	☐	☐	☐	☐	☐	☐	☐
Schedule system	☐	☐	☐	☐	☐	☐	☐
Quality system	☐	☐	☐	☐	☐	☐	☐
Off-site/pre construction	☐	☐	☐	☐	☐	☐	☐
Construction	☐	☐	☐	☐	☐	☐	☐
As-built documentation	☐	☐	☐	☐	☐	☐	☐
Facility start-up & life cycle support	☐	☐	☐	☐	☐	☐	☐

Automation/Integration (AI) Technology Effectiveness

On a scale of 0 to 10, with 0 indicating not effective and 10 indicating very effective, please assess ***the overall effectiveness of Automation/Integration Technology Practices*** on this project.

0	1	2	3	4	5	6	7	8	9	10	NA	UNK
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

5. Construction Productivity Metrics

Instructions for Computation of Actual Work-Hours and Rework-Hours

Actual work-hours are computed by the summation of all the account hours that are listed as **Direct** in the following table. All the account hours listed as **Indirect** are to be **excluded** from the actual work-hours that are submitted in the productivity data for the following sections. Actual work-hours should **include** hours for rework. If you track actual rework-hours, please record this information at the end of each section where requested. Please review this table completely before providing data in the following sections.

	Direct	**Indirect**	
Account	Direct Craft Labor	Accounting	Procurement
	Foreman	Area Superintendent	Process Equipment Maintenance
	General Foreman	Assistant Project Manager	Project Controls
	Load and Haul	Bus Drivers	Project Manager
	Oilers	Clerical	QA/QC
	Operating Engineer	Craft Planners	Quantity Surveyors
	Safety Meetings	Craft Superintendent	Receive and Offload
	Scaffolding	Craft Training	Recruiting
	Truck Drivers Direct	Crane Setup/take down	Safety
		Document Control	Safety Barricades
		Drug Testing	Security
		Equipment Coordinator	Show-up Time
		Evacuation Time	Site Construction Manager
		Field Administration Staff	Site Maintenance
		Field Engineer-Project	Subcontract Administrator
		Field Staff (Hourly)	Supervision (Hourly)
		Field Staff (Salary)	Surveying Crews
		Fire Watch	Temporary Facilities
		Flag Person	Temporary Utilities
		General Superintendent	Test Welders
		Hole Watch	Tool Room
		Janitorial	Truck Drivers Indirect
		Job Clean-Up	Warehouse
		Master Mechanic	Warehousing
		Material Control	Water Hauling
		Mobilization	
		Nomex Distribution	
		Orientation Time	
		Payroll Clerks/ Timekeepers	

5.1. Concrete

Instructions

Please complete the following tables indicating installed neat quantity and work-hours (**including rework**) for the categories appropriate to your project and indicate if the work performed for each category was subcontracted or not. If work performed for a category was both subcontracted and in-house, indicate the type that was more predominate. Also, please record the total rework-hours with source information if available where requested at the end of the section.

Include work hours for the following selected activities:
Loading material at the jobsite yard, hauling to, and unloading at the job work site; local layout, excavation and backfill, fabrication, installation, stripping and cleaning forms; field installation of reinforcing material; field installation of all embeds; all concrete placement, curing, finishing, rubbing, mud mats; and anchor bolt installation.

Do not include work hours for:
Piling, drilled piers, wellpoints and major de-watering, concrete fireproofing, batch plants, non-permanent roads and facilities, third party testing, mass excavations, rock excavations, site survey, q-deck, sheet piles, earthwork shoring, cold pour preparation, grouting, precast tees, panels, decks, vaults, manholes, etc.

Definitions

The **Installed Neat Quantity** of concrete is that concrete that is required for the specified slab, foundation, or structure provided in the project's plans and specifications and does not include any quantity of concrete that is used due to rework.
Refer to the section "**Instructions for Computation of Actual Work-Hours and Rework-Hours**" for an additional detailed listing of direct hours to be included and indirect hours that are to be excluded from the computation of the actual work-hours.

Slabs	None	Subcontracted (Yes or No)	Installed Quantity (cubic yards)	Actual Work-Hours (including rework) (hours)
On-Grade				
Elevated Slabs/On Deck				
Area Paving				
Total Slabs				

Foundations	None	Subcontracted (Yes or No)	Installed Quantity (cubic yards)	Actual Work-Hours (including rework) (hours)
< 5 cubic yards				
5 – 20 cubic yards				
21– 50 cubic yards				
> 50 cubic yards				
Total Foundations				

Concrete Structures	**None**	**Subcontracted (Yes or No)**	**Installed Quantity (cubic yards)**	**Actual Work-Hours (including rework) (hours)**
Concrete Structures				
This includes concrete structures, columns, beams, cooling tower basins, trenches, formed elevated slabs/structures, retaining walls, and drainage structures.				

Total Concrete	**None**	**Subcontracted (Yes or No)**	**Installed Quantity (cubic yards)**	**Actual Work-Hours (including rework) (hours)**
Total Concrete				
The total concrete quantity and work hours may be **greater than** the sum of totals for slabs, foundations and concrete structures if the project included concrete not in these categories.				

Rework-Hours

Source of Rework-Hours for Concrete	**Rework-Work (hours)**
Design	
Vendor	
Owner	
Contractor	
Other	
Total	

Concrete Repetitive Construction

If the project includes multiple similar components that allow construction efficiencies (i.e. based on learning curve, formwork reuse, etc.), estimate the percentage of the total quantity for concrete that was repeated.

Example: The total concrete quantity for a project is 5,000 CY. The design includes three identical foundations of 1,000 CY each. There are no other identical components. The estimated repeated quantity for concrete is:

$$\frac{2000\text{ CY}}{5000\text{ CY}} = 40\%$$

● No Response

○	○	○	○	○	○	○	○	○	○
< 10%	>= 10%	> 20%	> 30%	> 40%	> 50%	> 60%	> 70%	> 80%	> 90%

5.2. Structural Steel

Instructions

Please complete the following tables indicating installed quantity and work-hours (**including rework**) for the categories appropriate to your project and indicate if the work performed for each category was subcontracted or not. If work performed for a category was both subcontracted and in-house, indicate the type that was more predominate. Also, please record the total rework-hours with source information if available where requested at the end of the section.

This includes work-hours for the following selected activities:
Shake-out, transporting, erection, plumbing, leveling, bolting, and welding.

Do not include work-hours for:
Fabrication, demolition, and architectural work, such as roofing, siding and vents.

Definitions

The **Installed Quantity** of steel is that quantity of steel provided in the project's plans and specifications and does not include any quantity of steel that is used due to rework.
Refer to the section "**Instructions for Computation of Actual Work-Hours and Rework-Hours**" for an additional detailed listing of direct hours to be included and indirect hours that are to be excluded from the computation of the actual work-hours.

Structural Steel	None	Subcontracted (Yes or No)	Installed Quantity (tons)	Actual Work-Hours (including rework) (hours)
Structural Steel				
This includes trusses, columns, girders, beams, struts, girts, purlins, vertical and horizontal bracing, bolts, and nuts.				
Pipe Racks & Utility Bridges				
This includes steel structures outside the physical boundaries of a major structure, which is used to support pipe, conduit, and/or cable tray.				
Miscellaneous Steel				
This includes handrails, toeplate, grating, checker plate, stairs, ladders, cages, miscellaneous platforms, pre-mounted ladders and platforms, miscellaneous support steel including scab on supports, "T" and "H" type supports, trench covers, and Q decking.				
Total Structural Steel				

Rework-Hours

Source of Rework-Hours for Steel	Rework-Hours (hours)
Design	
Vendor	
Owner	
Contractor	
Other	
Total	

Structural Steel Repetitive Construction

If the project includes multiple similar components that allow construction efficiencies (i.e. based on learning curve, formwork reuse, etc.), estimate the percentage of the total quantity for structural steel that was repeated.

Example: The total concrete quantity for a project is 5,000 CY. The design includes three identical foundations of 1,000 CY each. There are no other identical components. The estimated repeated quantity for concrete is :

$$\frac{2000\text{ CY}}{5000\text{ CY}} = 40\%$$

● No Response									
○	○	○	○	○	○	○	○	○	○
< 10%	>= 10%	> 20%	> 30%	> 40%	> 50%	> 60%	> 70%	> 80%	> 90%

5.3. Electrical

Instructions

Please complete the following tables indicating installed quantity and work-hours **(including rework)** for the categories appropriate to your project and indicate if the work performed for each category was subcontracted or not. If work performed for a category was both subcontracted and in-house, indicate the type that was more predominate. Also, please record the total rework-hours with source information if available where requested at the end of the section.

This includes work-hours for the following selected activities:
Installation, testing, labeling, etc.

Definitions

The **Installed Quantity** of electrical equipment, devices, conduit and cable trays are the quantity of each provided in the project's plans and specifications and does not include any quantity that is used due to rework.

Refer to the section "**Instructions for Computation of Actual Work-Hours and Rework-Hours**" for an additional detailed listing of direct hours to be included and indirect hours that are to be excluded from the computation of the actual work-hours.

- Total Direct Electrical Work-Hours for This Project _________
- Total Connected Horsepower of Motors _________
- Number of Motors _________
- Total KVA Load of Project _________

Electrical Equipment and Devices	**None**	**Subcontracted (Yes or No)**	**Installed Quantity (each)**	**Actual Work-Hours (including rework) (hours)**
Panels and Small Devices				
This includes all labor for the installation of lighting and power panels, dry type transformers, control stations (pushbuttons, small local panels, etc.), welding receptacles and their supports. Count includes only actual electrical devices - not supports.				
Electrical Equipment 600V & Below				
Electrical Equipment Over 600V				
Total Electrical Equipment				
This includes all labor for the installation of transformers, switchgear, UPS systems, MCCs, DCS/PLC racks and panels, etc.				

Instructions for calculation of Weighted-Average Diameter of Conduit (Hyperlink)

Conduit	None	Subcontracted (Yes or No)	Weighted Average Diameter (inches)	Installed Quantity (lineal feet)	Actual Work Hours (including rework) (hours)
Exposed or Aboveground Conduit					
This includes all labor for installation of conduit, hangers, supports, fittings, flexible connections, marking, grounding jumpers, seals, boxes, etc. This excludes lighting conduit.					
Underground, Duct Bank or Embedded Conduit					
This includes all labor for installation of conduit, supports, grounding jumpers, etc. Does not include excavation, backfill, concrete, manholes, etc.					
Total Conduit					

Instructions for calculation of Weighted-Average Size of Cable Tray (Hyperlink)

Cable Tray	None	Subcontracted (Yes or No)	Weighted Average Size (width in inches)	Installed Quantity (lineal feet)	Actual Work Hours (including rework) (hours)
Cable Tray					
This includes all labor for the installation of tray, channel, supports, covers, grounding jumpers, marking, etc. It does not include fire stop or cable tray for instrument wire and cable.					

Wire and Cable	None	Subcontracted (Yes or No)	Installed Quantity (lineal feet)	Actual Work-Hours (including rework) (hours)
Power and Control Cable - 600V & below				
This includes all labor for the installation, termination, labeling, and testing of 600V and below power and control cable. It does not include heat-tracing cable.				
Power Cable – 5 & 15KV				
This includes all labor for the installation, termination, labeling, and testing of medium voltage power cables.				
Total Wire and Cable				

Other Electrical	None	Subcontracted (Yes or No)	Installed Quantity	Actual Work-Hours (including rework) (hours)
Lighting (each-Fixtures)				
This includes all labor for the installation of fixtures (including lamps and supports) and for the installation of conduit and wiring from the lighting panel to the fixtures. Includes any control equipment, switches, conduit, wiring and accessories installed on the load side of the lighting panel. Installation of lighting panels is included in Panels and Small Devices and power feeder wiring for the panel is included in Power and Control Cable - 600V.				
Grounding (lineal feet)				
This includes all the labor for the installation of cable, ground rods, connectors and all accessories for the installation of conduit and wiring from the lighting panel to the fixtures. Includes work hours for the installation of ground cables pulled into cable trays, duct banks, and installed exposed in electric or other rooms. The footage is based on the total footage of ground cable installed.				
Electrical Heat Tracing (lineal feet)				
This includes the labor for the installation of electric heat trace cable, power feeds to the cable, control accessories, end of line devices, connectors, tape or other strapping/support materials, and any other items needed to complete the heat trace system. Footage is based on the lineal footage of process and utility piping heat traced.				

Rework-Hours

Source of Rework-Hours for Electrical	Rework-Hours (hours)
Design	
Vendor	
Owner	
Contractor	
Other	
Total	

5.4. Piping

Instructions

Please complete the following tables indicating the weighted-average diameter in inches, the installed quantity, percent shop fabricated, percent hot and cold, and work-hours (**including rework**) for the categories appropriate to your project and indicate if the work performed for each category was subcontracted or not. If work performed for a category was both subcontracted and in-house, indicate the type that was more predominate. Also, please record the total rework-hours with source information if available where requested at the end of the section.

Include work-hours for the following selected activities:

Erecting and installing piping, including welding, valves, in-line specials, flushing/hydro testing, tie-ins (excluding hot taps), material handling (from the laydown yard to the field), in-line devices, specialties, equipment operators, and hangers & supports.

Do not include work-hours for:

Non-destructive evaluation (NDE), steam tracing, stress relieving, underground piping, offloading pipe as it is received, commissioning, and field fabrication of large bore.

Definitions

The **Installed Quantity** of piping is that piping specified in the project's plans and specifications and does not include any quantity of piping that is used due to rework.

Refer to the section "**Instructions for Computation of Actual Work-Hours and Rework-Hours**" for an additional detailed listing of direct hours to be included and indirect hours that are to be excluded from the computation of the actual work-hours.

Instructions for calculation of Small Bore Weighted-Average Diameter (Hyperlink)

Small Bore (2-1/2" and Smaller)

- Field and Shop Fabricated and Field Run (Excludes Tubing)

Small Bore	None	Subcontracted (Yes or No)	Weighted-Average Diameter (inches)	Installed Quantity (lineal feet)	Actual Work-Hours (including rework) (hours)	Percent Shop Fabricated (%)
Carbon Steel						
Stainless Steel						
Chrome						
Other Alloys						
Total Small Bore						

In the following sections for large bore piping the following definitions apply for hot and cold piping. **Hot piping** is that piping which has a design temperature greater than 250 degrees Fahrenheit. **Cold piping** is that piping which has a design temperature less than minus 20 degrees Fahrenheit.

Instructions for calculation of ISBL and OSBL Large Bore Weighted-Average Diameter (Hyperlink)

Inside Battery Limits (ISBL) Large Bore (3" and Larger) (Excludes Tubing)

Large Bore (ISBL)	**None**	**Subcontracted (Yes or No)**	**Weighted-Average Diameter (inches)**	**Average Wall Thickness (schedule)**	**Installed Quantity (lineal feet)**	**Actual Work-Hours (including rework) (hours)**	**% Shop Fabricated (%)**	**% Hot and Cold (%)**
Carbon Steel								
Stainless Steel								
Chrome								
Other Alloys								
Total Large Bore (ISBL)								

Outside Battery Limits (OSBL) Large Bore (3" and Larger) (Excludes Tubing)

Large Bore (OSBL)	**None**	**Subcontracted (Yes or No)**	**Weighted-Average Diameter (inches)**	**Average Wall Thickness (schedule)**	**Installed Quantity (lineal feet)**	**Actual Work-Hours (including rework) (hours)**	**% Shop Fabricated (%)**	**% Hot and Cold (%)**
Carbon Steel								
Stainless Steel								
Chrome								
Other Alloys								
Total Large Bore (OSBL)								

Rework-Hours

Source of Rework-Hours for Piping	**Rework-Hours (hours)**
Design	
Vendor	
Owner	
Contractor	
Other	
Total	

APPENDIX B: CII BENCHMARKING AND MATRIX PROGRAM SURVEY FOR SMALL PROJECTS (PARTS)

SMALL PROJECTS QUESTIONNAIRE VERSION 1.3a

1. General Information

Your Company Name: ____

Project ID: ____

Please provide the Name that you will use to refer to this Project: _______________

Project Location: Domestic (US States or Canadian Provinces) ________________

Project Location: International (Country) ___________________________________

Contact Person: (Name of knowledgeable person) ___________________________

Contact's Phone: ______________________

Contact's Fax: ________________________

Contact's E-mail Address: ____

Expected project Completion Date (MM/DD/Year):___________________________

1.1. Project Description

Principle Type of Project:

Choose a Project Type which <u>**best**</u> describes the project from the categories below. If the project is a mixture of two or more of those listed, select the principle type. If the project type does not appear in the list, select other under the appropriate industry group and specify the project type.

Heavy Industrial

☐ Chemical Manufacturing
☐ Electrical (Generating)
☐ Environmental
☐ Metals Refining/Processing
☐ Mining
☐ Natural Gas Processing
☐ Oil Exploration/Production
☐ Oil Refining
☐ Oil Sands Mining/Extraction
☐ Oil Sands SAGD
☐ Oil Sands Upgrading
☐ Cogeneration
☐ Pulp and Paper
☐ Pipeline
☐ Gas Distribution
☐ Other Heavy Industrial
Please specify:____________________.

Light Industrial

☐ Automotive Manufacturing
☐ Consumer Products Manufacturing
☐ Foods
☐ Microelectronics Manufacturing
☐ Office Products Manufacturing
☐ Pharmaceutical Manufacturing
☐ Pharmaceutical Labs
☐ Clean Room (Hi-Tech)
☐ Other Light Industrial
Please specify:____________________.

Buildings

☐ Communications Center
☐ Courthouse
☐ Dormitory/Hotel/Housing/Residential
☐ Embassy
☐ Low rise Office (≤3 floors)
☐ High rise Office (>3 floors)
☐ Hospital
☐ Laboratory
☐ Maintenance Facilities
☐ Movie Theatre
☐ Parking Garage
☐ Physical Fitness Center
☐ Prison
☐ Restaurant/Nightclub
☐ Retail Building
☐ School
☐ Warehouse
☐ Other Buildings
Please specify:______________________.

Infrastructure

☐ Airport
☐ Electrical Distribution
☐ Flood Control
☐ Highway
☐ Marine Facilities
☐ Navigation
☐ Rail
☐ Tunneling
☐ Water/Wastewater
☐ Telecom, Wide Area Network
☐ Other Infrastructure
Please specify:______________________.

1.2. Project Nature

Select the category that best describes the nature of this project. If your project is a combination of these natures, select the category that you would like your project to be benchmarked against. Please see the glossary for definitions.

The Project Nature was:
☐ Grass Roots
☐ Modernization
☐ Addition
☐ Maintenance
☐ Other Project Nature (Please describe):_______________

1.2a Project Drivers

Select the primary driver for this project. Assume safety is a given for all projects.

The primary driver was:
☐ Cost
☐ Schedule
☐ Meeting Product Specifications
☐ Production Capacity
☐ Other (Please describe): ____________________________
☐ No Primary Driver

Construction performance (cost, schedule, and safety) during project turnarounds, shutdowns, and outages may be impacted by schedule demands of the turnaround.

These turnarounds may be schedule or unscheduled. Please complete the blocks below to indicate the percentage of construction work completed during turnaround.

1. Percent construction during **scheduled turnaround:** ________ %
2. Percent construction during **unscheduled turnaround:** ________ %
3. Percent construction during **non-turnaround:** ________ %

Note: the percentages should add up to 100 %

1.3. Typical Project

Projects submitted for benchmarking should be representative of the projects that you execute, i.e., not impacted by extraordinary factors that might influence performance or practice use metrics. If the project is not representative, it can still be submitted to be scored, however, please let us know by checking the appropriate box below.

☐ **Typical** ☐ **Not Typical**

If project is not typical, Please provide reason:

____

1.4. Project Delivery System

Please choose the project delivery system from those listed below that most closely characterizes the delivery system used for your project. If more than one delivery system was used, select the primary system.

	Delivery System	**Description**
☐	Traditional Design-Bid-Build	Serial sequence of design and construction phases; Owner contracts separately with designer and constructor.
☐	Design-Build (or EPC)	Overlapped sequence of design and construction phase; procurement normally begins during design; owner contracts with Design-Build (or EPC) contractor.
☐	CM at Risk	Overlapped sequence of design and construction phases; procurement normally begins during design; owner contracts separately with designer and CM at Risk (constructor).
☐	Multiple Design-Build	Overlapped sequence of design and construction phases; procurement normally begins during design; owner contracts with two Design-Build (or EPC) contractors, one for process and one for facilities.
☐	Parallel Primes	Overlapped sequence of design and construction phases; Procurement normally begins during design. Owner contracts separately with designer and multiple prime constructors.
☐	Other	Please describe:

Did you use a Construction Manager not at Risk in conjunction with the selected delivery system?
Yes________________ No________________

3.10. Automation Integration (AI) Technology

Many IT tools and systems are being used in project execution today. Many more tools and systems will be available soon that will further improve and enhance project execution and small projects. The benefits of using technology on projects include: reduced costs, shorter schedules, improved quality, reduced rework, better communication, enhanced information exchange and resource utilization, better informed team members, and smaller multi-skilled teams for project execution.

A	Referring to the **use levels** below, indicate the level that the following work functions were automated (utilized computer automated systems).	None 0	Some 1	Moderate 2	Nearly Full 3	Full 4	NA / UNK
	Detailed Design	☐	☐	☐	☐	☐	☐
	Procurement	☐	☐	☐	☐	☐	☐
	Construction	☐	☐	☐	☐	☐	☐
	Maintenance	☐	☐	☐	☐	☐	☐
	Project Management (Including Controls)	☐	☐	☐	☐	☐	☐

<u>USE LEVELS</u>

- **None/Minimal:** Little or no utilization beyond e-mail.
- **Some:** "Office" equivalent software, 2D CAD for detailed design.
- **Moderate:** Standalone electronic/automated engineering discipline (3D CAD) and project services systems.
- **Nearly Full:** Some automated input/output from multiple databases with automated engineering discipline design and project services systems.
- **Full:** Fully or nearly fully automated systems dominate execution of all work functions.

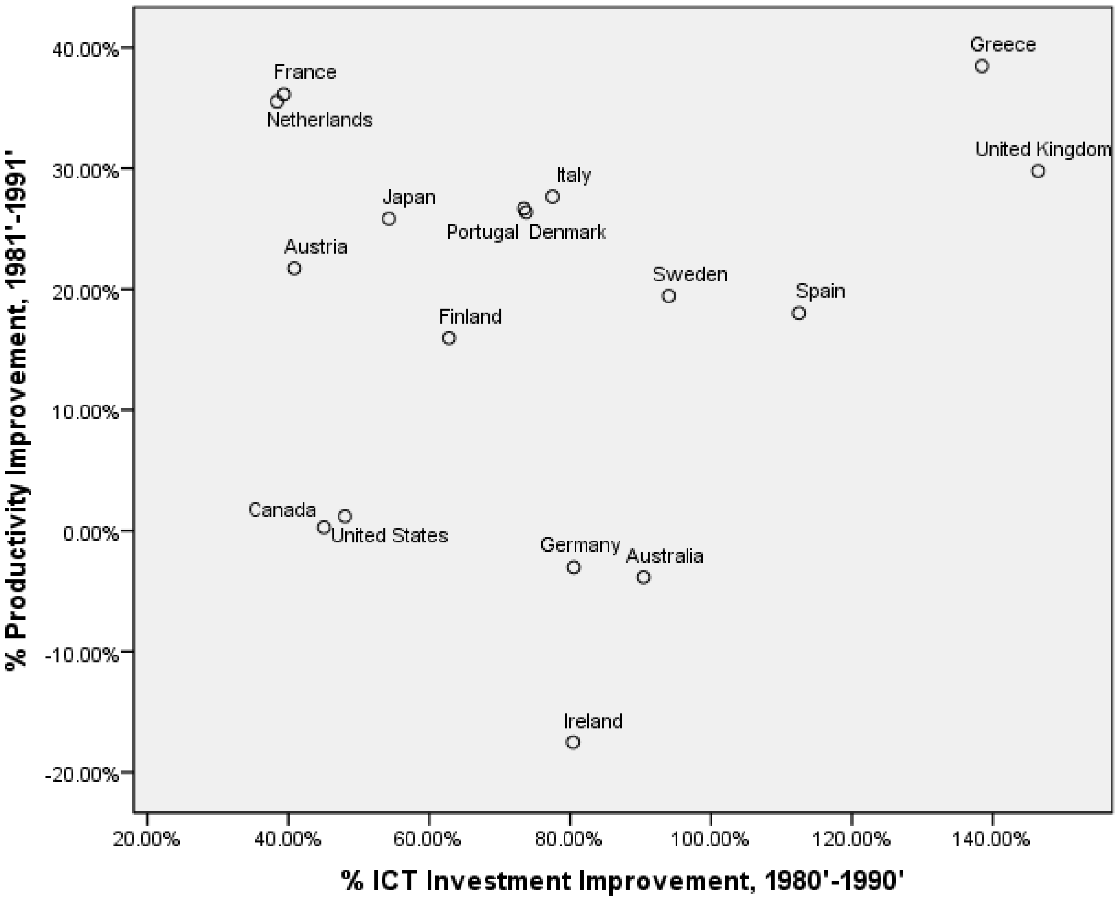
B	Referring to the **integration levels** below, indicate how well the work functions were ***integrated across all other*** work functions.	None 0	Some 1	Moderate 2	Nearly Full 3	Full 4	NA / UNK
	Detailed Design	☐	☐	☐	☐	☐	☐
	Procurement	☐	☐	☐	☐	☐	☐
	Construction	☐	☐	☐	☐	☐	☐
	Maintenance	☐	☐	☐	☐	☐	☐
	Project Management (Including Controls)	☐	☐	☐	☐	☐	☐

<u>INTEGRATION LEVELS</u>

- **None/Minimal:** Little or no integration of electronic systems/applications.
- **Some:** Manual transfer of information via hardcopy or email.
- **Moderate:** Manual and some electronic transfer between automated systems.
- **Nearly Full:** Most systems are integrated with significant human intervention for tracking inputs/outputs.
- **Full:** All information is stored on a network system accessible to all automation systems and users. All routine communications are automated. The automated process and discipline design systems are fully integrated into 3D design, supply management, and project services systems (cost, schedule, quality, and safety).

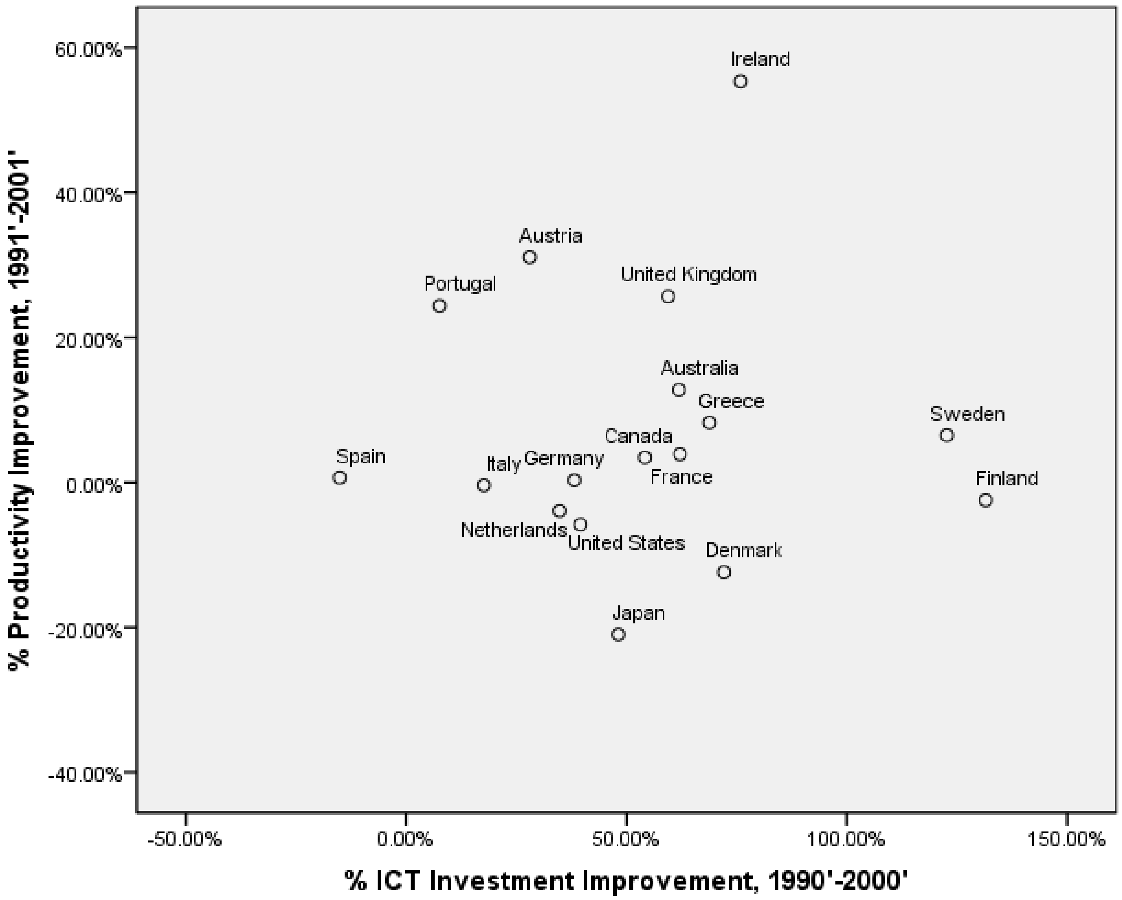
APPENDIX C: MAJOR STATISTICAL ANALYSIS OUTPUT

Scatter Plot and Spearman Rank Correlation (Section 4.4)

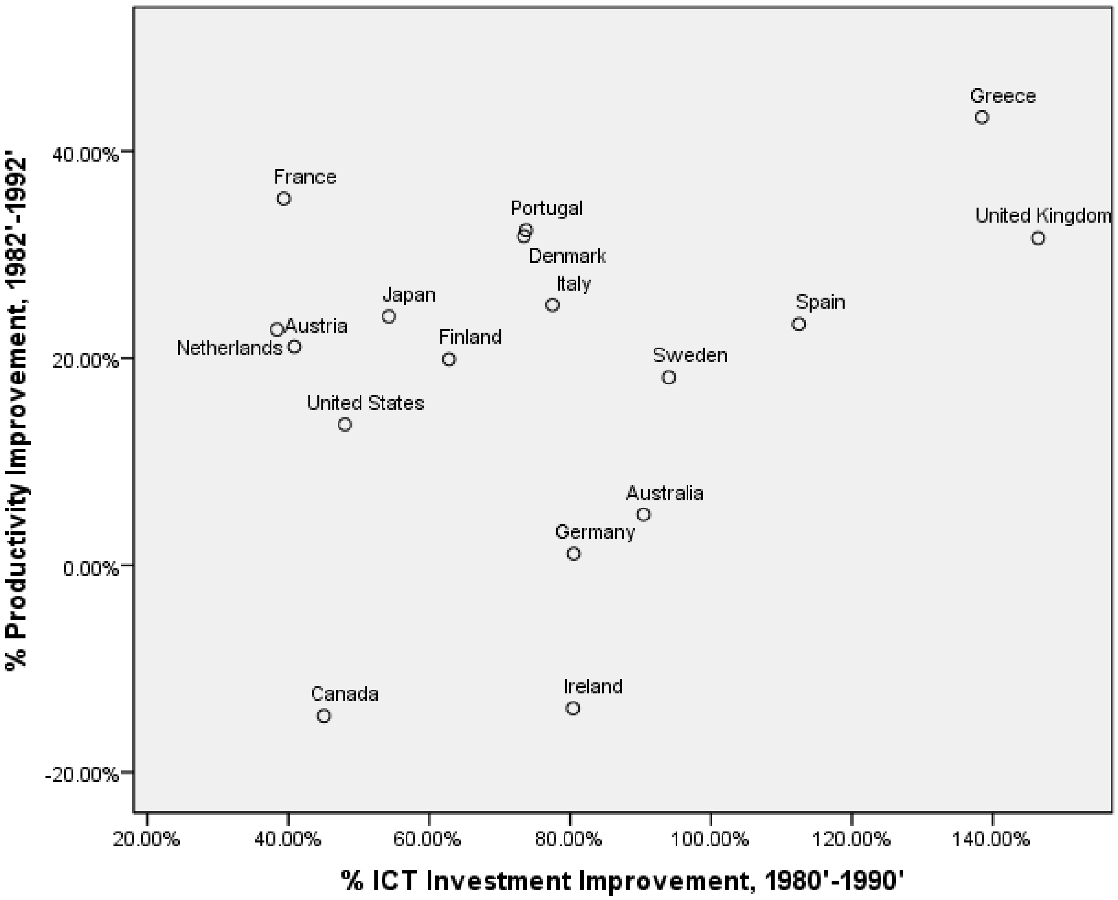


Correlations

			% Productivity Improvement, 1981'-1991'
Spearman's rho	% Productivity Improvement, 1981'-1991'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	-.086
		Sig. (2-tailed)	.743
		N	17

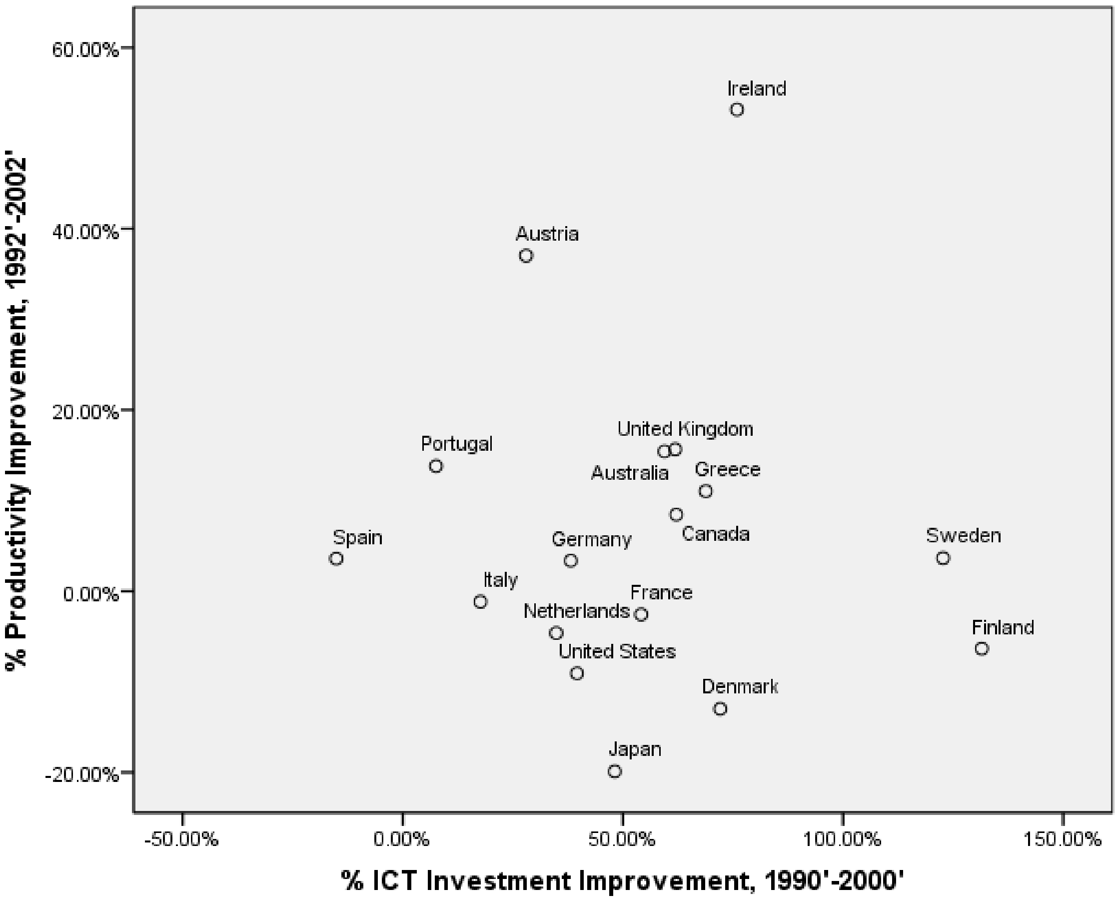


			% Productivity Improvement, 1991'-2001'
Spearman's rho	% Productivity Improvement, 1991'-2001'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1990'-2000'	Correlation Coefficient	.064
		Sig. (2-tailed)	.808
		N	17



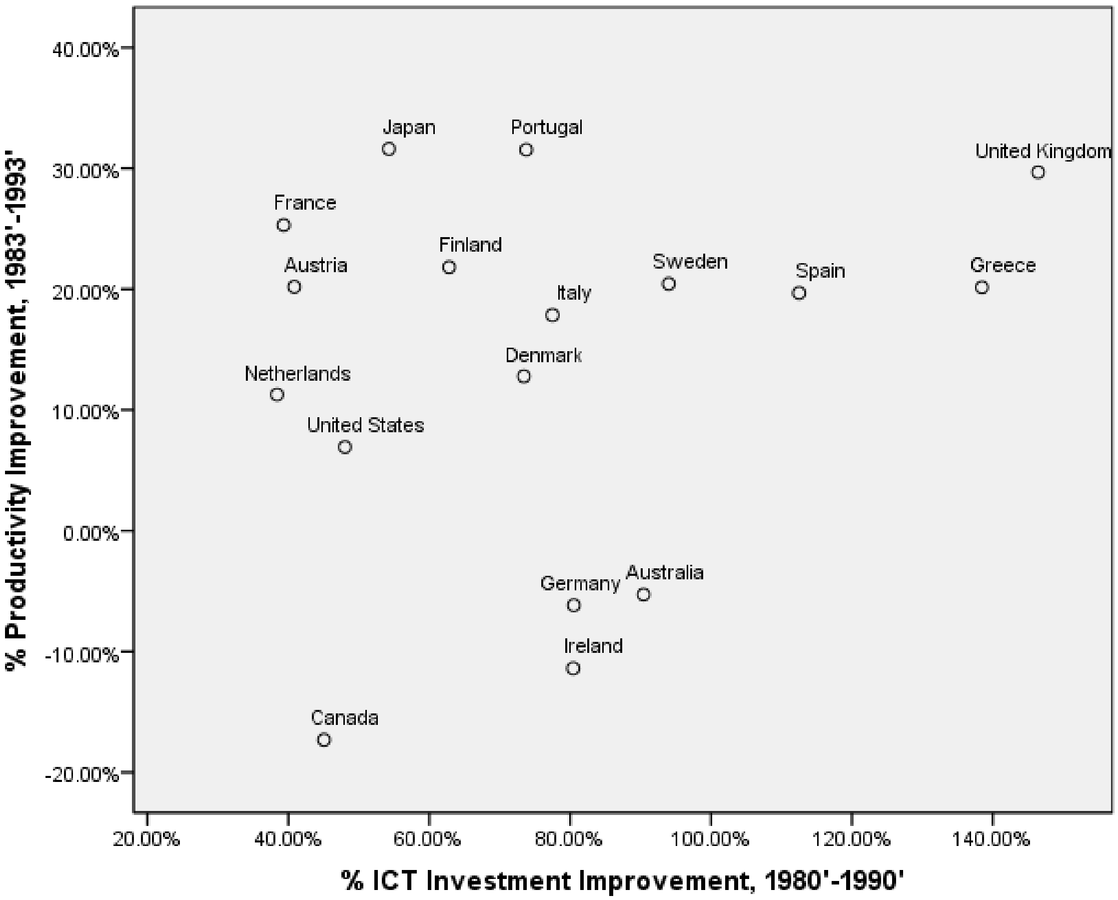
Correlations

			% Productivity Improvement, 1982'-1992'
Spearman's rho	% Productivity Improvement, 1982'-1992'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	.088
		Sig. (2-tailed)	.736
		N	17



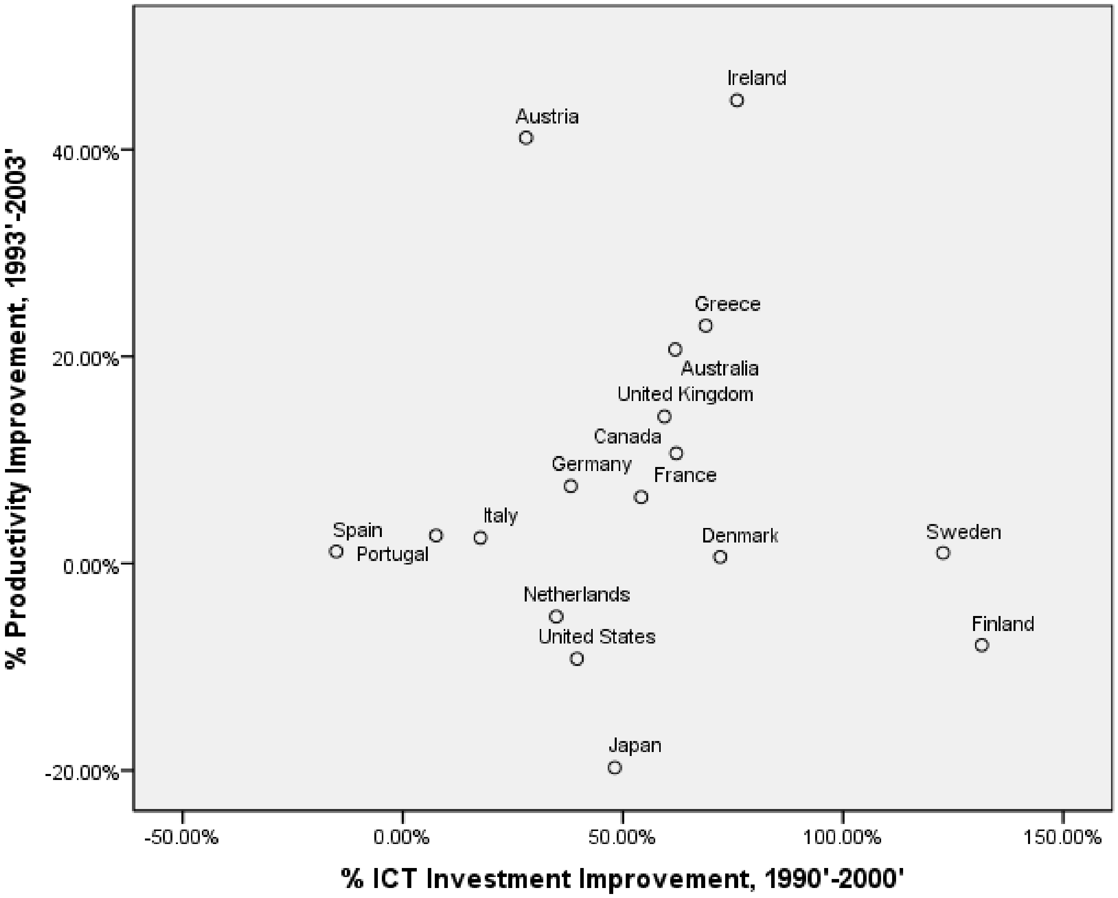
Correlations

			% Productivity Improvement, 1992'-2002'
Spearman's rho	% Productivity Improvement, 1992'-2002'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1990'-2000'	Correlation Coefficient	.007
		Sig. (2-tailed)	.978
		N	17



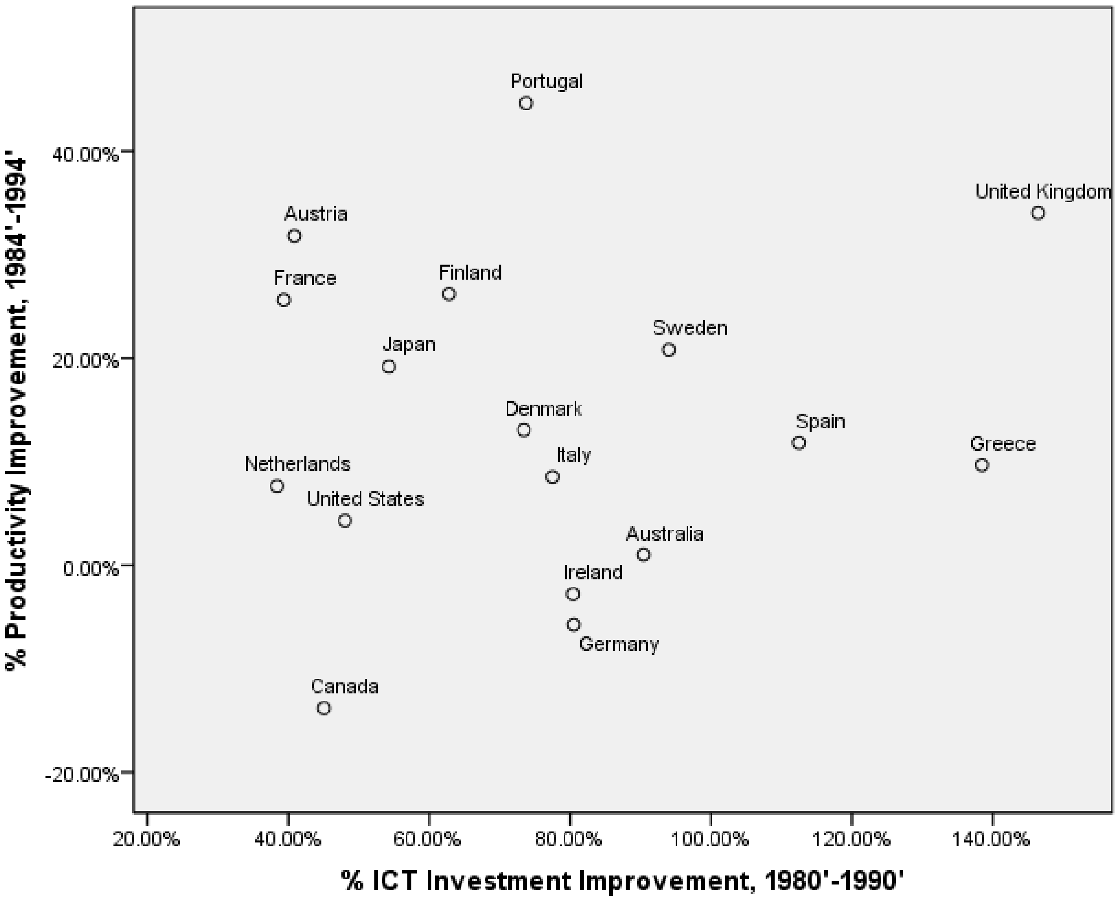
Correlations

			% ICT Investment Improvement, 1980'-1990'
Spearman's rho	% Productivity Improvement, 1983'-1993'	Correlation Coefficient	.049
		Sig. (2-tailed)	.852
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17



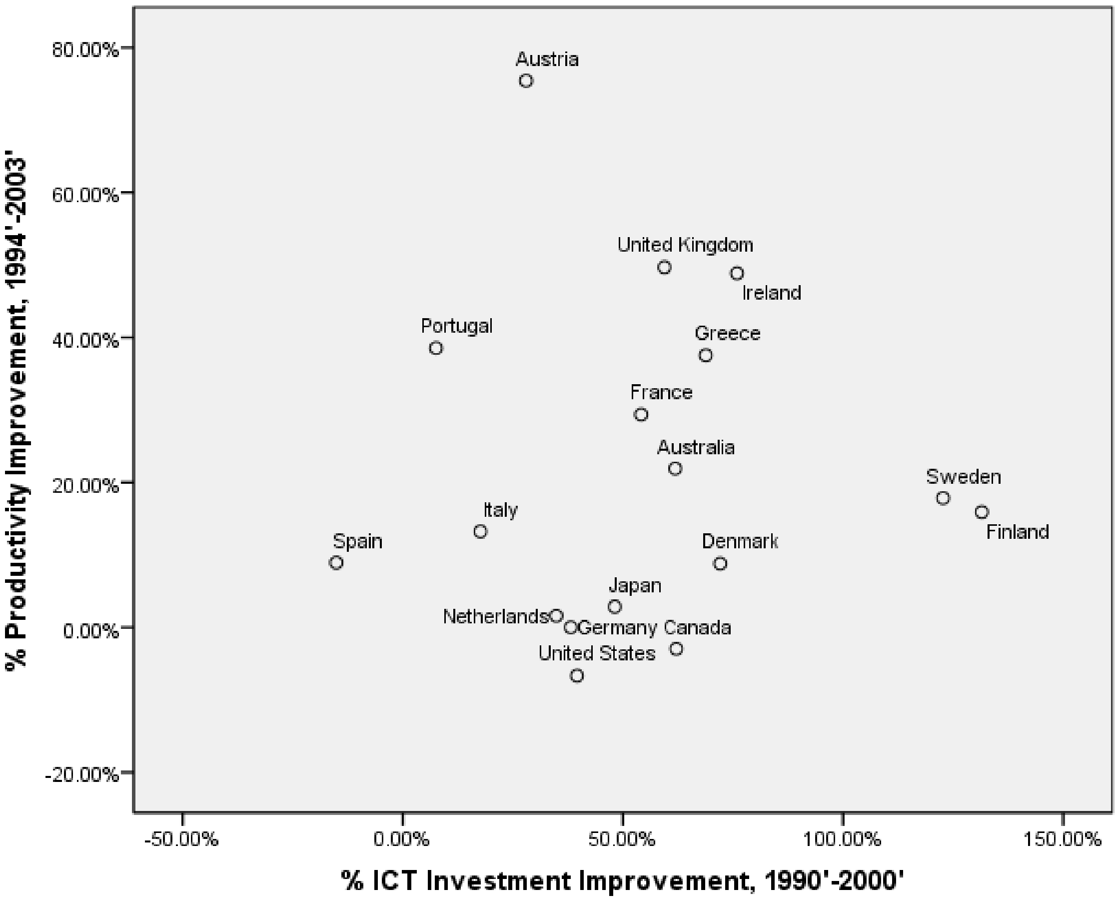
Correlations

			% Productivity Improvement, 1993'-2003'
Spearman's rho	% Productivity Improvement, 1993'-2003'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1990'-2000'	Correlation Coefficient	.071
		Sig. (2-tailed)	.786
		N	17



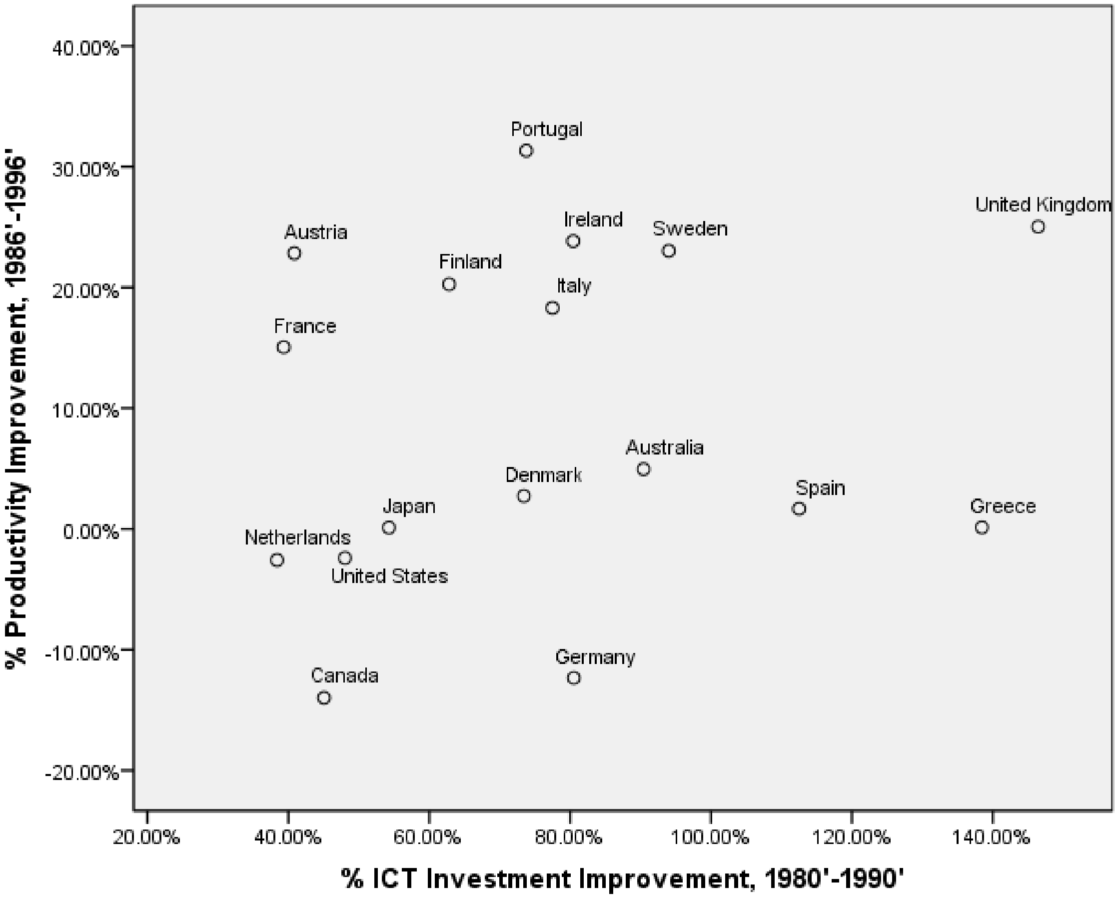
Correlations

			% Productivity Improvement, 1984'-1994'
Spearman's rho	% Productivity Improvement, 1984'-1994'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	.020
		Sig. (2-tailed)	.940
		N	17



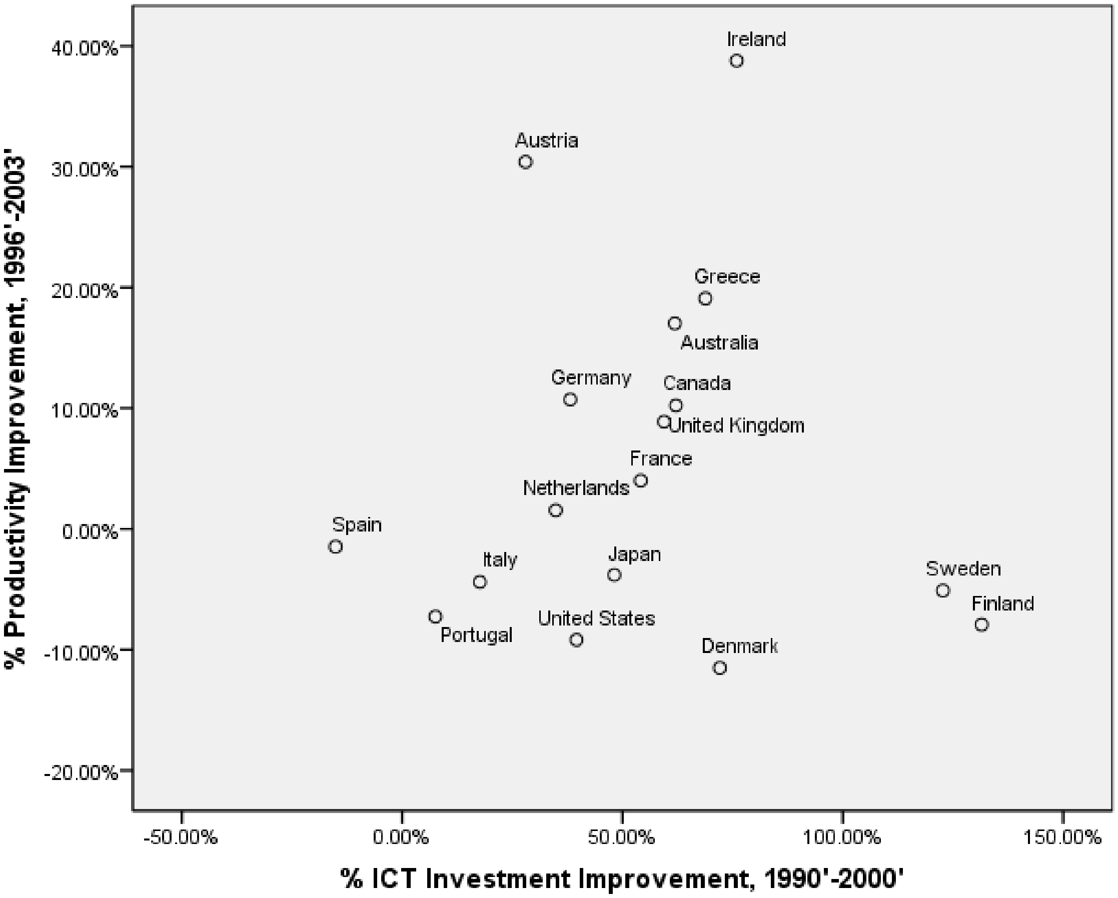
Correlations

			% Productivity Improvement, 1994'-2003'
Spearman's rho	% Productivity Improvement, 1994'-2003'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1990'-2000'	Correlation Coefficient	.096
		Sig. (2-tailed)	.715
		N	17



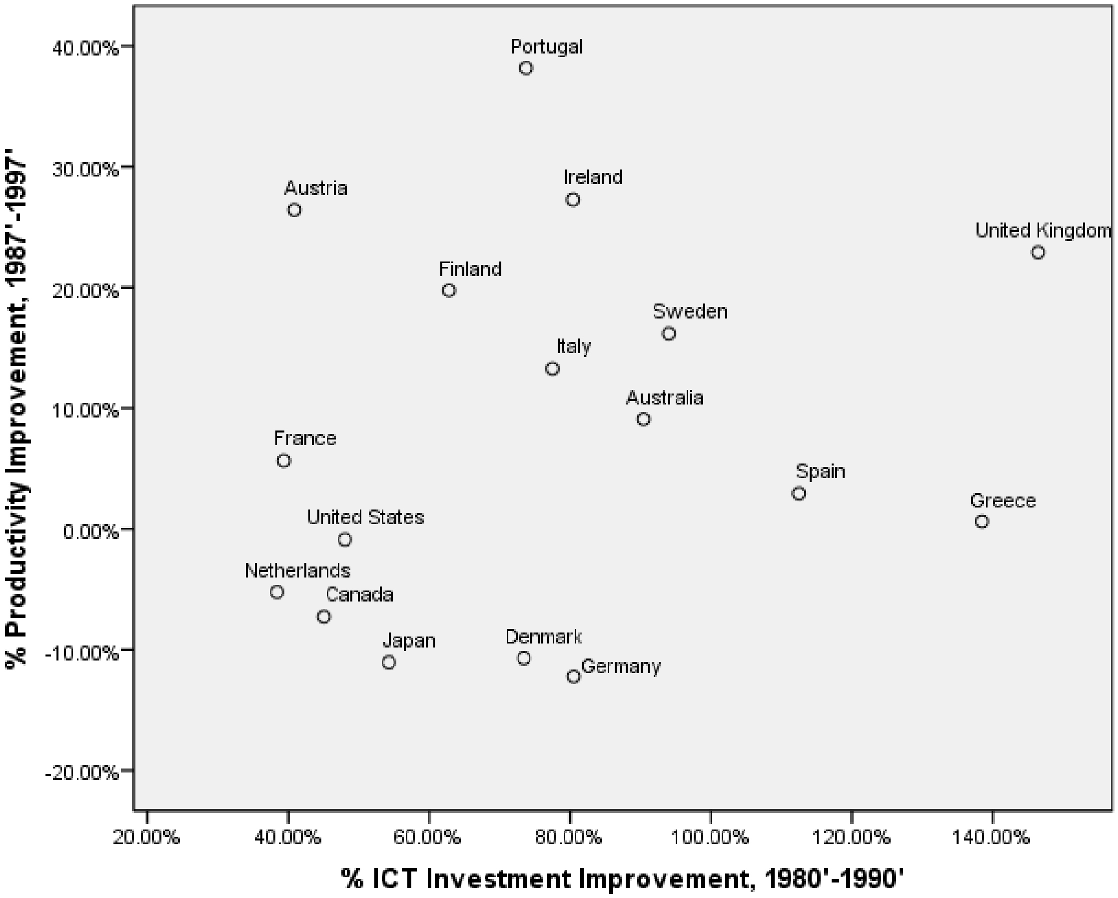
Correlations

			% Productivity Improvement, 1986'-1996'
Spearman's rho	% Productivity Improvement, 1986'-1996'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	.306
		Sig. (2-tailed)	.232
		N	17



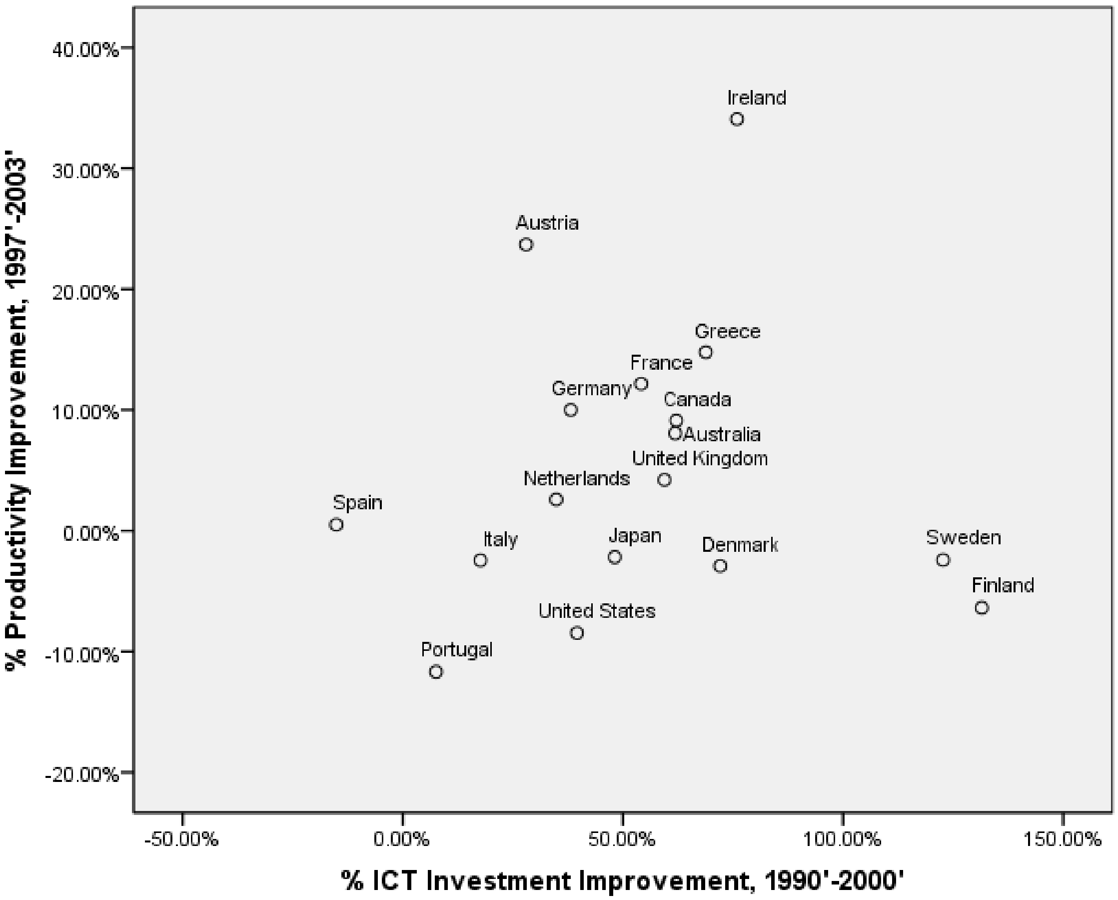
Correlations

			% Productivity Improvement, 1996'-2003'
Spearman's rho	% Productivity Improvement, 1996'-2003'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1990'-2000'	Correlation Coefficient	.017
		Sig. (2-tailed)	.948
		N	17



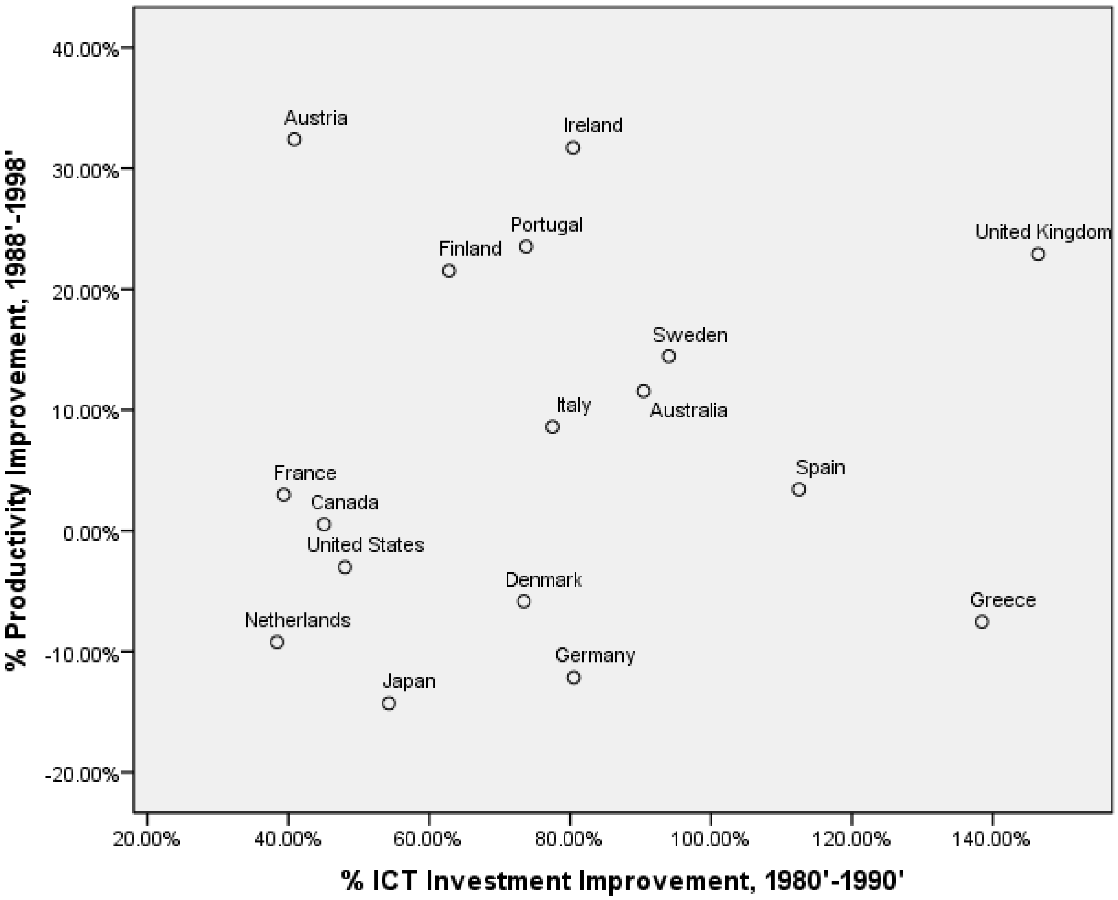
Correlations

			% ICT Investment Improvement, 1980'-1990'
Spearman's rho	% Productivity Improvement, 1987'-1997'	Correlation Coefficient	.203
		Sig. (2-tailed)	.434
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17



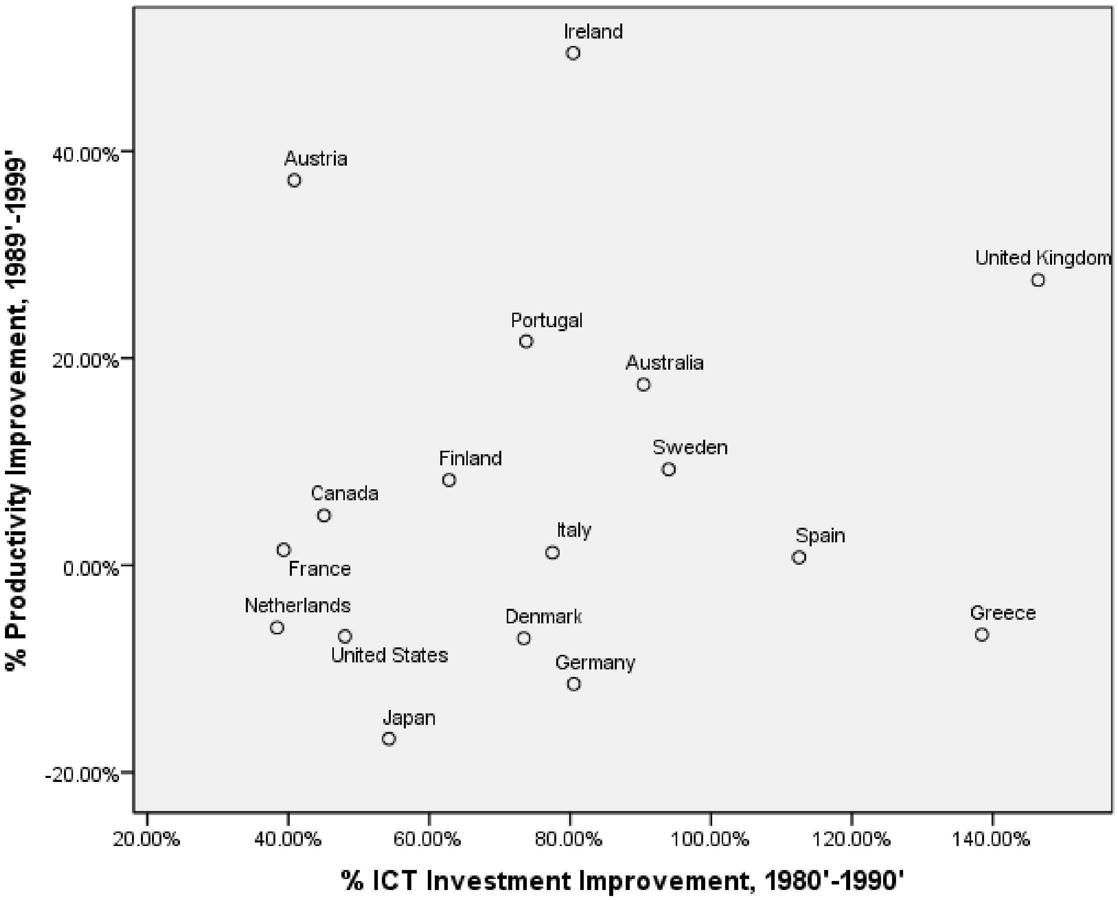
Correlations

			% Productivity Improvement, 1997'-2003'
Spearman's rho	% Productivity Improvement, 1997'-2003'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1990'-2000'	Correlation Coefficient	.120
		Sig. (2-tailed)	.646
		N	17



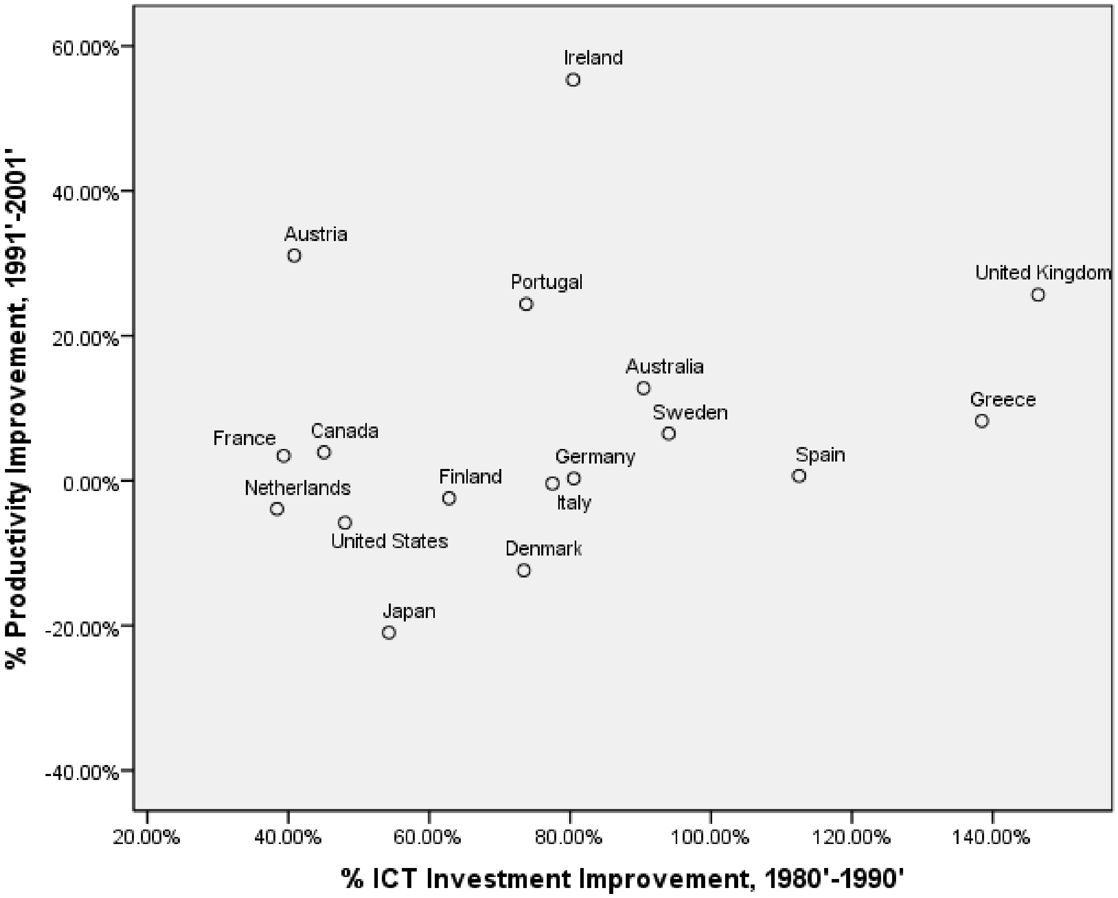
Correlations

			% Productivity Improvement, 1988'-1998'
Spearman's rho	% Productivity Improvement, 1988'-1998'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	.174
		Sig. (2-tailed)	.504
		N	17



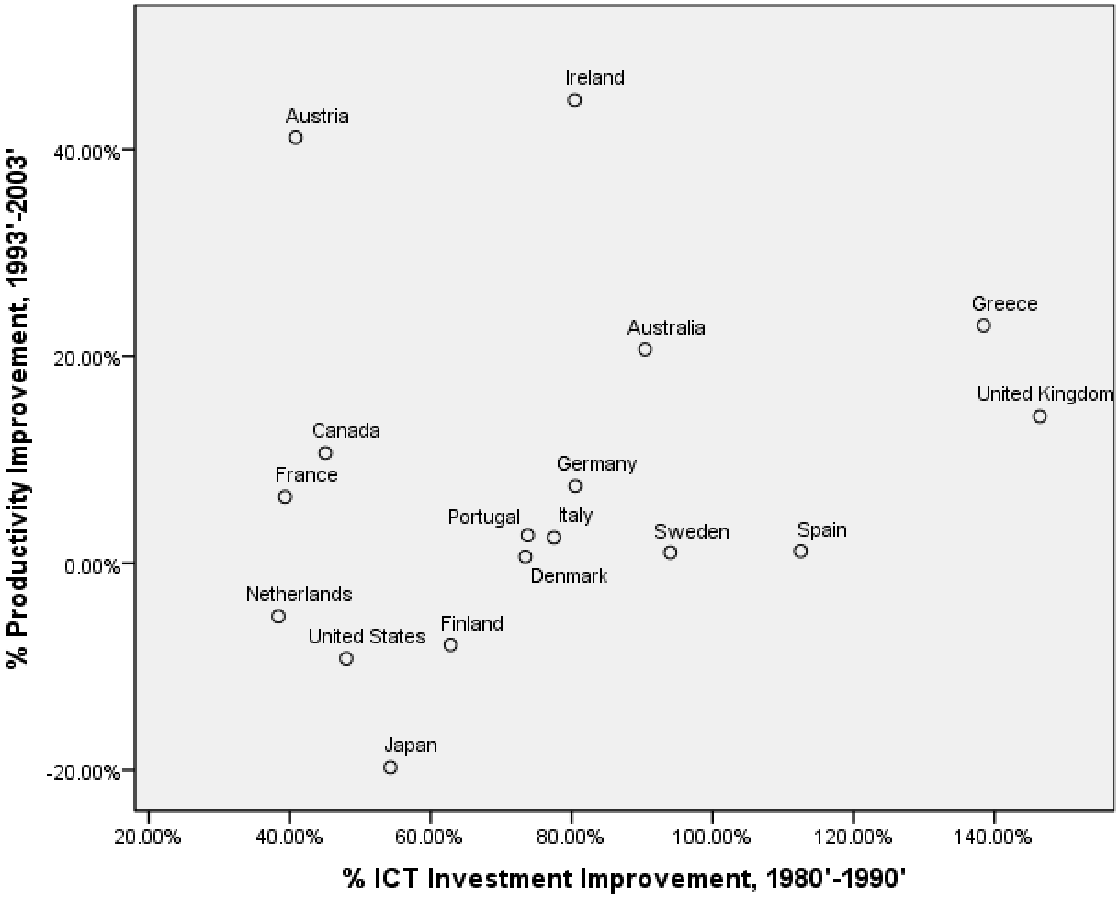
Correlations

			% ICT Investment Improvement, 1980'-1990'
Spearman's rho	% Productivity Improvement, 1989'-1999'	Correlation Coefficient	.137
		Sig. (2-tailed)	.599
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17



Correlations

			% ICT Investment Improvement, 1980'-1990'
Spearman's rho	% Productivity Improvement, 1991'-2001'	Correlation Coefficient	.373
		Sig. (2-tailed)	.141
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17



Correlations

			% Productivity Improvement, 1993'-2003'
Spearman's rho	% Productivity Improvement, 1993'-2003'	Correlation Coefficient	1.000
		Sig. (2-tailed)	.
		N	17
	% ICT Investment Improvement, 1980'-1990'	Correlation Coefficient	.324
		Sig. (2-tailed)	.205
		N	17

Factor Analysis for Automation Usage (Section 6.4.1)

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.839
Bartlett's Test of Sphericity	Approx. Chi-Square	329.601
	df	78
	Sig.	.000

Communalities

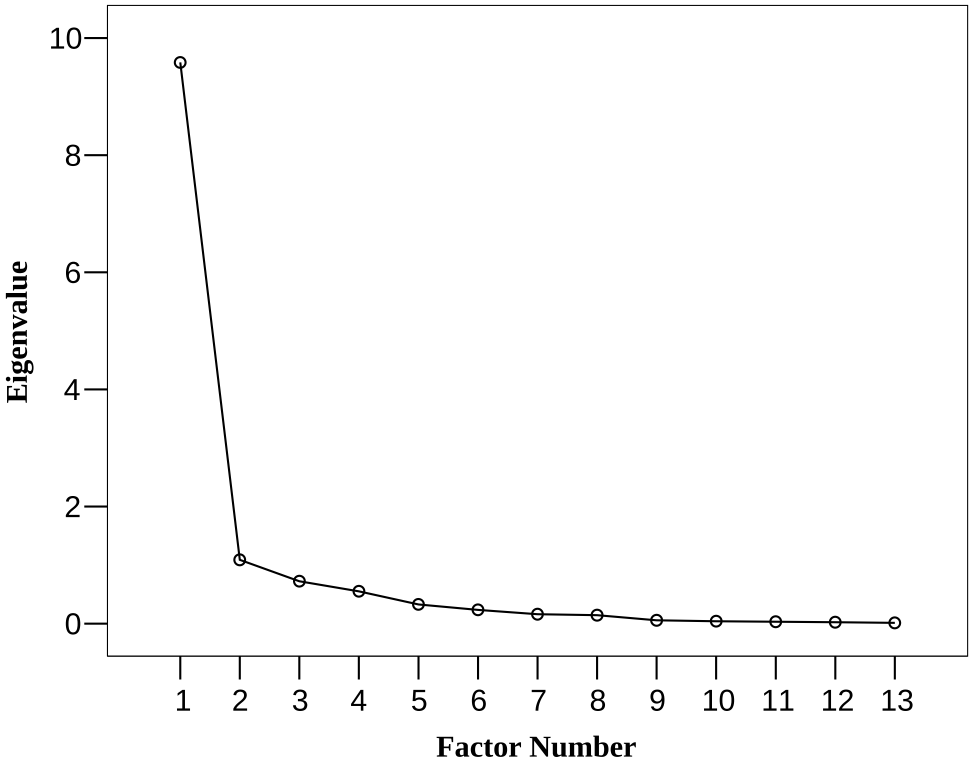
	Initial	Extraction
Auto_Business Planning & Analysis	1.000	.851
Auto_Conceptual Definition & Design	1.000	.905
Auto_Project Definition & Facility Design	1.000	.790
Auto_Supply Management	1.000	.608
Auto_Coordination Systems	1.000	.874
Auto_Communication Systems	1.000	.884
Auto_Cost Systems	1.000	.867
Auto_Schedule Systems	1.000	.886
Auto_Quality Systems	1.000	.855
Auto_Offsite/pre-construction	1.000	.681
Auto_Construction	1.000	.821
Auto_As-built Documentation	1.000	.844
Auto_Facility Start-up and Life Cycle Support	1.000	.807

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	9.583	73.714	73.714	9.583	73.714	73.714	6.416	49.357	49.357
2	1.091	8.391	82.106	1.091	8.391	82.106	4.257	32.748	82.106
3	.726	5.582	87.688						
4	.554	4.263	91.951						
5	.329	2.534	94.485						
6	.236	1.817	96.302						
7	.162	1.248	97.550						
8	.145	1.118	98.668						
9	.058	.448	99.116						
10	.042	.324	99.440						
11	.034	.258	99.698						
12	.025	.195	99.893						
13	.014	.107	100.000						

Extraction Method: Principal Component Analysis.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Eigenvalue
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Factor Number

Component Matrix(a)

	Component	
	1	2
Auto_Business Planning & Analysis	.672	.633
Auto_Conceptual Definition & Design	.911	.274
Auto_Project Definition & Facility Design	.788	.410
Auto_Supply Management	.735	-.260
Auto_Coordination Systems	.935	.009
Auto_Communication Systems	.940	.001
Auto_Cost Systems	.871	-.328
Auto_Schedule Systems	.914	-.225
Auto_Quality Systems	.902	-.205
Auto_Offsite/pre-construction	.825	.029
Auto_Construction	.897	-.129
Auto_As-built Documentation	.885	.247
Auto_Facility Start-up and Life Cycle Support	.841	-.317

Extraction Method: Principal Component Analysis.
a 2 components extracted.

Rotated Component Matrix(a)

	Component	
	1	2
Auto_Business Planning & Analysis	.146	.911
Auto_Conceptual Definition & Design	.554	.773
Auto_Project Definition & Facility Design	.374	.806
Auto_Supply Management	.741	.243
Auto_Coordination Systems	.735	.578
Auto_Communication Systems	.744	.574
Auto_Cost Systems	.890	.272
Auto_Schedule Systems	.861	.380
Auto_Quality Systems	.839	.389
Auto_Offsite/pre-construction	.636	.527
Auto_Construction	.789	.446
Auto_As-built Documentation	.549	.736
Auto_Facility Start-up and Life Cycle Support	.859	.262

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a Rotation converged in 3 iterations.

Component Transformation Matrix

Component	1	2
1	.792	.611
2	-.611	.792

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Component Score Coefficient Matrix

	Component	
	1	2
Auto_Business Planning & Analysis	-.299	.502
Auto_Conceptual Definition & Design	-.078	.257
Auto_Project Definition & Facility Design	-.165	.348
Auto_Supply Management	.206	-.142
Auto_Coordination Systems	.072	.066
Auto_Communication Systems	.077	.060
Auto_Cost Systems	.256	-.183
Auto_Schedule Systems	.202	-.105
Auto_Quality Systems	.189	-.091
Auto_Offsite/pre-construction	.052	.074
Auto_Construction	.146	-.037
Auto_As-built Documentation	-.065	.236
Auto_Facility Start-up and Life Cycle Support	.247	-.177

Extraction Method: Principal Axis Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

Component Score Covariance Matrix

Component	1	2
1	1.000	.000
2	.000	1.000

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

Factor Analysis for Integration Usage (Section 6.4.2)

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.579
Bartlett's Test of Sphericity	Approx. Chi-Square	371.590
	df	78
	Sig.	.000

Communalities

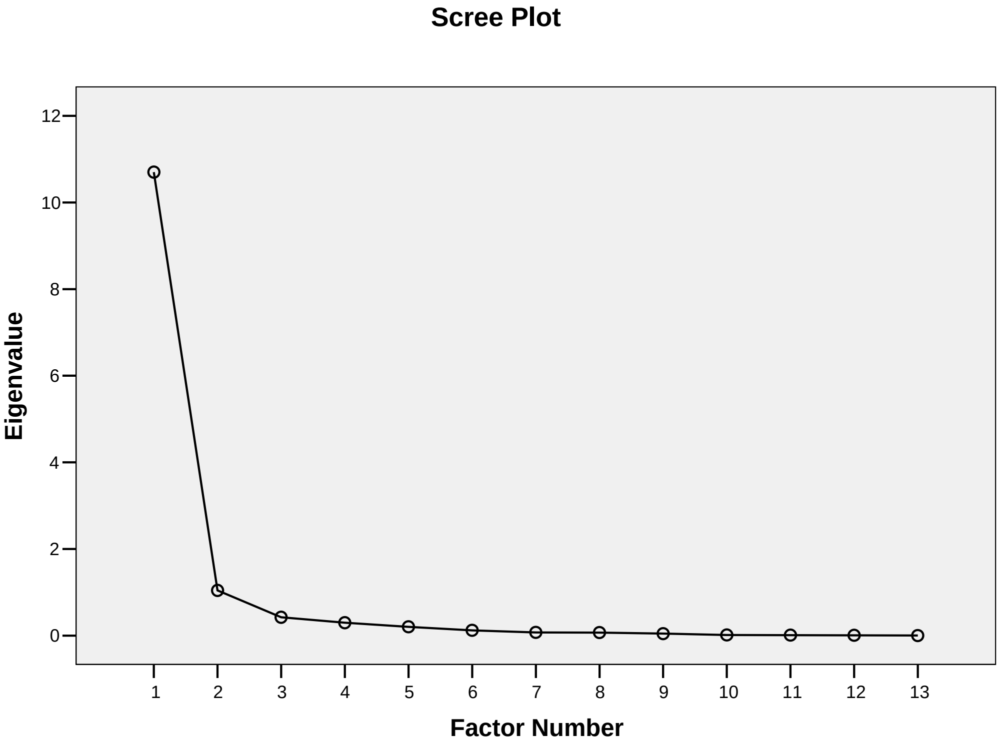
	Initial	Extraction
Inte_Business Planning & Analysis	.996	.938
Inte_Conceptual Definition & Design	.995	.900
Inte_Project Definition & Facility Design	.979	.912
Inte_Supply Management	.991	.755
Inte_Coordination Systems	.996	.859
Inte_Communication Systems	.999	.921
Inte_Cost Systems	.969	.898
Inte_Schedule Systems	.993	.824
Inte_Quality Systems	.973	.881
Inte_Offsite/pre-construction	.983	.835
Inte_Construction	.997	.926
Inte_As-built Documentation	1.000	.986
Inte_Facility Start-up and Life Cycle Support	.997	.912

Extraction Method: Principal Axis Factoring.

Total Variance Explained

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	10.701	82.316	82.316	10.591	81.466	81.466	6.895	53.038	53.038
2	1.043	8.022	90.338	.956	7.353	88.819	4.652	35.781	88.819
3	.422	3.243	93.582						
4	.296	2.276	95.857						
5	.202	1.550	97.408						
6	.121	.931	98.338						
7	.073	.561	98.899						
8	.069	.532	99.431						
9	.045	.347	99.777						
10	.014	.105	99.882						
11	.009	.072	99.954						
12	.006	.044	99.998						
13	.000	.002	100.000						

Extraction Method: Principal Axis Factoring.


Scree Plot
Eigenvalue
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13
Factor Number

Factor Matrix(a)

	Factor	
	1	2
Inte_Business Planning & Analysis	.837	.487
Inte_Conceptual Definition & Design	.869	.380
Inte_Project Definition & Facility Design	.934	.198
Inte_Supply Management	.864	-.086
Inte_Coordination Systems	.907	-.194
Inte_Communication Systems	.959	-.036
Inte_Cost Systems	.905	-.282
Inte_Schedule Systems	.897	-.137
Inte_Quality Systems	.897	-.277
Inte_offsite/pre-construction	.913	-.014
Inte_Construction	.953	-.136
Inte_As-built Documentation	.955	-.272
Inte_facility start-up and life cycle support	.831	.470

Extraction Method: Principal Axis Factoring.
a 2 factors extracted. 6 iterations required.

Rotated Factor Matrix(a)

	Factor	
	1	2
Inte_Business Planning & Analysis	.356	.901
Inte_Conceptual Definition & Design	.447	.837
Inte_Project Definition & Facility Design	.611	.734
Inte_Supply Management	.732	.467
Inte_Coordination Systems	.832	.410
Inte_Communication Systems	.775	.566
Inte_Cost Systems	.885	.339
Inte_Schedule Systems	.789	.448
Inte_Quality Systems	.876	.338
Inte_offsite/pre-construction	.726	.554
Inte_Construction	.832	.483
Inte_As-built Documentation	.918	.378
Inte_facility start-up and life cycle support	.361	.884

Extraction Method: Principal Axis Factoring.
Rotation Method: Varimax with Kaiser Normalization.
a Rotation converged in 3 iterations.

Factor Transformation Matrix

Factor	1	2
1	.785	.619
2	-.619	.785

Extraction Method: Principal Axis Factoring.
Rotation Method: Varimax with Kaiser Normalization.

Component Score Coefficient Matrix

	Component	
	1	2
Inte_Business Planning & Analysis	-.233	.425
Inte_Conceptual Definition & Design	-.176	.356
Inte_Project Definition & Facility Design	-.056	.213
Inte_Supply Management	.127	-.029
Inte_Coordination Systems	.190	-.104
Inte_Communication Systems	.090	.031
Inte_Cost Systems	.242	-.171
Inte_Schedule Systems	.158	-.065
Inte_Quality Systems	.242	-.172
Inte_Offsite/pre-construction	.074	.045
Inte_Construction	.152	-.049
Inte_As-built Documentation	.224	-.141
Inte_Facility Start-up and Life Cycle Support	-.230	.420

Extraction Method: Principal Axis Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

Component Score Covariance Matrix

Component	1	2
1	1.000	.000
2	.000	1.000

Extraction Method: Principal Axis Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Component Scores.

Regression Analysis of Automation Use on Productivity (Section 6.5.1)

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	AuPC1scale (a)	.	Enter

a All requested variables entered.
b Dependent Variable: Norm_concrete

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.290(a)	.084	.068	2.268752

a Predictors: (Constant), AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	26.895	1	26.895	5.225	.026[a]
	Residual	293.392	57	5.147		
	Total	320.287	58			

a. Predictors: (Constant), AuPC1scale

b. Dependent Variable: Norm_concrete

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.177	1.695		4.235	.000
	AuPC1scale	-1.175	.514	-.290	-2.286	.026

a. Dependent Variable: Norm_concrete

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	AuPC2scale (a)	.	Enter

a All requested variables entered.
b Dependent Variable: Norm_concrete

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.017(a)	.000	-.017	2.370129

a Predictors: (Constant), AuPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.089	1	.089	.016	.900[a]
	Residual	320.198	57	5.618		
	Total	320.287	58			

a. Predictors: (Constant), AuPC2scale

b. Dependent Variable: Norm_concrete

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	3.615	2.035		1.776	.081
	AuPC2scale	-.084	.667	-.017	-.126	.900

a. Dependent Variable: Norm_concrete

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale, Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_concrete

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.290[a]	.084	.051	2.288819

a. Predictors: (Constant), AuPC2scale, AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	26.920	2	13.460	2.569	.086[a]
	Residual	293.367	56	5.239		
	Total	320.287	58			

a. Predictors: (Constant), AuPC2scale, AuPC1scale

b. Dependent Variable: Norm_concrete

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.310	2.555		2.861	.006
	AuPC1scale	-1.174	.519	-.290	-2.263	.028
	AuPC2scale	-.045	.644	-.009	-.070	.944

a. Dependent Variable: Norm_concrete

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	Au PC1scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_steel

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.263[a]	.069	.052	2.010947

a. Predictors: (Constant), AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15.945	1	15.945	3.943	.052[a]
	Residual	214.327	53	4.044		
	Total	230.272	54			

a. Predictors: (Constant), AuPC1scale

b. Dependent Variable: Norm_steel

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.300	1.855		3.935	.000
	AuPC1scale	-1.053	.530	-.263	-1.986	.052

a. Dependent Variable: Norm_steel

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	AuPC2scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_steel

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.281[a]	.079	.061	2.000581

a. Predictors: (Constant), AuPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	18.149	1	18.149	4.535	.038[a]
	Residual	212.123	53	4.002		
	Total	230.272	54			

a. Predictors: (Constant), AuPC2scale

b. Dependent Variable: Norm_steel

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.825	1.976		3.959	.000
	AuPC2scale	-1.351	.634	-.281	-2.129	.038

a. Dependent Variable: Norm_steel

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale, Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_steel

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.452[a]	.204	.173	1.877590

a. Predictors: (Constant), AuPC2scale, AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	46.955	2	23.477	6.660	.003[a]
	Residual	183.318	52	3.525		
	Total	230.272	54			

a. Predictors: (Constant), AuPC2scale, AuPC1scale

b. Dependent Variable: Norm_steel

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	14.416	2.959		4.872	.000
	AuPC1scale	-1.472	.515	-.368	-2.858	.006
	AuPC2scale	-1.836	.619	-.382	-2.966	.005

a. Dependent Variable: Norm_steel

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_electrical

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.358[a]	.128	.113	2.642648

a. Predictors: (Constant), AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	59.418	1	59.418	8.508	.005[a]
	Residual	405.048	58	6.984		
	Total	464.466	59			

a. Predictors: (Constant), AuPC1scale

b. Dependent Variable: Norm_electrical

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	11.180	2.660		4.204	.000
	AuPC1scale	-2.140	.734	-.358	-2.917	.005

a. Dependent Variable: Norm_electrical

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_electrical

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.206[a]	.042	.026	2.769257

a. Predictors: (Constant), AuPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	19.676	1	19.676	2.566	.115[a]
	Residual	444.790	58	7.669		
	Total	464.466	59			

a. Predictors: (Constant), AuPC2scale

b. Dependent Variable: Norm_electrical

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.004	2.209		-.002	.998
	AuPC2scale	1.126	.703	.206	1.602	.115

a. Dependent Variable: Norm_electrical

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale, Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_electrical

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.358[a]	.128	.097	2.665661

a. Predictors: (Constant), AuPC2scale, AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	59.438	2	29.719	4.182	.020[a]
	Residual	405.028	57	7.106		
	Total	464.466	59			

a. Predictors: (Constant), AuPC2scale, AuPC1scale

b. Dependent Variable: Norm_electrical

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	10.949	5.095		2.149	.036
	AuPC1scale	-2.113	.893	-.353	-2.366	.021
	AuPC2scale	.044	.817	.008	.053	.958

a. Dependent Variable: Norm_electrical

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_piping

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.262[a]	.069	.035	2.771828

a. Predictors: (Constant), AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15.836	1	15.836	2.061	.162[a]
	Residual	215.125	28	7.683		
	Total	230.961	29			

a. Predictors: (Constant), AuPC1scale

b. Dependent Variable: Norm_piping

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.097	3.086		-.355	.725
	AuPC1scale	1.320	.919	.262	1.436	.162

a. Dependent Variable: Norm_piping

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_piping

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.060[a]	.004	-.032	2.866843

a. Predictors: (Constant), AuPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.835	1	.835	.102	.752[a]
	Residual	230.126	28	8.219		
	Total	230.961	29			

a. Predictors: (Constant), AuPC2scale

b. Dependent Variable: Norm_piping

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.608	4.218		1.092	.284
	AuPC2scale	-.439	1.378	-.060	-.319	.752

a. Dependent Variable: Norm_piping

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale, Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_piping

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.289[a]	.084	.016	2.799858

a. Predictors: (Constant), AuPC2scale, AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	19.303	2	9.651	1.231	.308[a]
	Residual	211.659	27	7.839		
	Total	230.961	29			

a. Predictors: (Constant), AuPC2scale, AuPC1scale

b. Dependent Variable: Norm_piping

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.219	4.674		.261	.796
	AuPC1scale	1.463	.953	.290	1.535	.136
	AuPC2scale	-.919	1.382	-.126	-.665	.512

a. Dependent Variable: Norm_piping

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Au PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: NormPro_4trade

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.188[a]	.035	.031	2.442979

a. Predictors: (Constant), AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	44.170	1	44.170	7.401	.007[a]
	Residual	1205.566	202	5.968		
	Total	1249.736	203			

a. Predictors: (Constant), AuPC1scale

b. Dependent Variable: NormPro_4trade

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	6.397	1.091		5.862	.000
	AuPC1scale	-.858	.315	-.188	-2.720	.007

a. Dependent Variable: NormPro_4trade

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	Au PC2scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: NormPro_4trade

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.008[a]	.000	-.005	2.487254

a. Predictors: (Constant), AuPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.077	1	.077	.012	.911[a]
	Residual	1249.659	202	6.186		
	Total	1249.736	203			

a. Predictors: (Constant), AuPC2scale

b. Dependent Variable: NormPro_4trade

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	3.335	1.179		2.829	.005
	AuPC2scale	.042	.381	.008	.111	.911

a. Dependent Variable: NormPro_4trade

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	AuPC2scale, AuPC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: NormPro_4trade

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.189[a]	.036	.026	2.448340

[a] Predictors: (Constant), AuPC2scale, AuPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	44.868	2	22.434	3.743	.025[a]
	Residual	1204.868	201	5.994		
	Total	1249.736	203			

[a] Predictors: (Constant), AuPC2scale, AuPC1scale

[b] Dependent Variable: NormPro_4trade

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	6.856	1.734		3.954	.000
	AuPC1scale	-.876	.321	-.192	-2.734	.007
	AuPC2scale	-.130	.380	-.024	-.341	.733

[a] Dependent Variable: NormPro_4trade

Regression Analysis of Integration Use on Productivity (Section 6.5.2)

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	In PC1scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_concrete

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.246[a]	.060	.040	2.302749

a. Predictors: (Constant), InPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15.363	1	15.363	2.897	.096[a]
	Residual	238.619	45	5.303		
	Total	253.982	46			

a. Predictors: (Constant), InPC1scale

b. Dependent Variable: Norm_concrete

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.055	2.137		3.302	.002
	InPC1scale	-1.102	.647	-.246	-1.702	.096

a. Dependent Variable: Norm_concrete

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	In PC2scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_concrete

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.326[a]	.106	.086	2.245928

a. Predictors: (Constant), InPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	26.994	1	26.994	5.351	.025[a]
	Residual	226.989	45	5.044		
	Total	253.982	46			

a. Predictors: (Constant), InPC2scale

b. Dependent Variable: Norm_concrete

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.785	1.897		4.104	.000
	InPC2scale	-1.448	.626	-.326	-2.313	.025

a. Dependent Variable: Norm_concrete

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	ln PC2scale, ln PC1scale[a]	.	Enter

[a] All requested variables entered.

[b] Dependent Variable: Norm_concrete

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.434[a]	.188	.152	2.164325

[a] Predictors: (Constant), lnPC2scale, lnPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	47.873	2	23.937	5.110	.010[a]
	Residual	206.109	44	4.684		
	Total	253.982	46			

[a] Predictors: (Constant), lnPC2scale, lnPC1scale

[b] Dependent Variable: Norm_concrete

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	12.457	2.870		4.340	.000
	lnPC1scale	-1.294	.613	-.289	-2.111	.040
	lnPC2scale	-1.600	.608	-.360	-2.634	.012

[a] Dependent Variable: Norm_concrete

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	ln PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_steel

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.492[a]	.242	.223	1.988313

a. Predictors: (Constant), lnPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	49.270	1	49.270	12.463	.001[a]
	Residual	154.182	39	3.953		
	Total	203.453	40			

a. Predictors: (Constant), lnPC1scale

b. Dependent Variable: Norm_steel

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	10.582	2.025		5.226	.000
	lnPC1scale	-2.090	.592	-.492	-3.530	.001

a. Dependent Variable: Norm_steel

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	In PC2scale [a]	.	Enter

[a] All requested variables entered.

[b] Dependent Variable: Norm_steel

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.274[a]	.075	.052	2.196380

[a] Predictors: (Constant), InPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15.313	1	15.313	3.174	.083[a]
	Residual	188.139	39	4.824		
	Total	203.453	40			

[a] Predictors: (Constant), InPC2scale

[b] Dependent Variable: Norm_steel

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.424	2.239		-.189	.851
	InPC2scale	1.277	.717	.274	1.782	.083

[a] Dependent Variable: Norm_steel

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	In PC2scale, In PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_steel

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.497[a]	.247	.207	2.008170

a. Predictors: (Constant), InPC2scale, InPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	50.208	2	25.104	6.225	.005[a]
	Residual	153.244	38	4.033		
	Total	203.453	40			

a. Predictors: (Constant), InPC2scale, InPC1scale

b. Dependent Variable: Norm_steel

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	9.032	3.811		2.370	.023
	InPC1scale	-1.952	.663	-.459	-2.942	.006
	InPC2scale	.351	.727	.075	.482	.632

a. Dependent Variable: Norm_steel

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	In PC1scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_electrical

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.403[a]	.162	.143	2.689858

a. Predictors: (Constant), InPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	60.366	1	60.366	8.343	.006[a]
	Residual	311.119	43	7.235		
	Total	371.486	44			

a. Predictors: (Constant), InPC1scale

b. Dependent Variable: Norm_electrical

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	14.820	3.934		3.767	.000
	InPC1scale	-3.154	1.092	-.403	-2.888	.006

a. Dependent Variable: Norm_electrical

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	ln PC2scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_electrical

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.105[a]	.011	-.012	2.922931

a. Predictors: (Constant), lnPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.114	1	4.114	.482	.491[a]
	Residual	367.372	43	8.544		
	Total	371.486	44			

a. Predictors: (Constant), lnPC2scale

b. Dependent Variable: Norm_electrical

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	6.389	4.164		1.534	.132
	lnPC2scale	-.945	1.362	-.105	-.694	.491

a. Dependent Variable: Norm_electrical

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	ln PC2scale, ln PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_electrical

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.417[a]	.174	.135	2.702762

a. Predictors: (Constant), lnPC2scale, lnPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	64.679	2	32.339	4.427	.018[a]
	Residual	306.807	42	7.305		
	Total	371.486	44			

a. Predictors: (Constant), lnPC2scale, lnPC1scale

b. Dependent Variable: Norm_electrical

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	17.782	5.521		3.221	.002
	lnPC1scale	-3.160	1.097	-.404	-2.879	.006
	lnPC2scale	-.967	1.259	-.108	-.768	.447

a. Dependent Variable: Norm_electrical

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	In PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_piping

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.171[a]	.029	-.019	2.583047

a. Predictors: (Constant), InPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.033	1	4.033	.604	.446[a]
	Residual	133.443	20	6.672		
	Total	137.476	21			

a. Predictors: (Constant), InPC1scale

b. Dependent Variable: Norm_piping

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.354	3.500		.101	.921
	InPC1scale	.807	1.038	.171	.777	.446

a. Dependent Variable: Norm_piping

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	ln PC2scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_piping

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.245[a]	.060	.013	2.541987

a. Predictors: (Constant), lnPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	8.242	1	8.242	1.275	.272[a]
	Residual	129.234	20	6.462		
	Total	137.476	21			

a. Predictors: (Constant), lnPC2scale

b. Dependent Variable: Norm_piping

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.012	3.558		1.971	.063
	lnPC2scale	-1.266	1.121	-.245	-1.129	.272

a. Dependent Variable: Norm_piping

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	ln PC2scale, ln PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Norm_piping

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.271[a]	.074	-.024	2.589100

a. Predictors: (Constant), lnPC2scale, lnPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	10.110	2	5.055	.754	.484[a]
	Residual	127.365	19	6.703		
	Total	137.476	21			

a. Predictors: (Constant), lnPC2scale, lnPC1scale

b. Dependent Variable: Norm_piping

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.668	5.731		.815	.425
	lnPC1scale	.565	1.071	.120	.528	.604
	lnPC2scale	-1.119	1.175	-.216	-.952	.353

a. Dependent Variable: Norm_piping

Variables Entered/Removed [b]

Model	Variables Entered	Variables Removed	Method
1	In PC1scale [a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: NormPro_4trade

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.233[a]	.054	.048	2.449131

a. Predictors: (Constant), InPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	52.688	1	52.688	8.784	.004[a]
	Residual	917.731	153	5.998		
	Total	970.419	154			

a. Predictors: (Constant), InPC1scale

b. Dependent Variable: NormPro_4trade

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.392	1.350		5.475	.000
	InPC1scale	-1.166	.393	-.233	-2.964	.004

a. Dependent Variable: NormPro_4trade

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	In PC2scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: NormPro_4trade

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.118[a]	.014	.007	2.500860

a. Predictors: (Constant), lnPC2scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	13.511	1	13.511	2.160	.144[a]
	Residual	956.908	153	6.254		
	Total	970.419	154			

a. Predictors: (Constant), lnPC2scale

b. Dependent Variable: NormPro_4trade

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	5.401	1.354		3.988	.000
	lnPC2scale	-.646	.439	-.118	-1.470	.144

a. Dependent Variable: NormPro_4trade

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	ln PC2scale, ln PC1scale[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: NormPro_4trade

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.287[a]	.083	.071	2.420067

a. Predictors: (Constant), lnPC2scale, lnPC1scale

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	80.197	2	40.098	6.847	.001[a]
	Residual	890.222	152	5.857		
	Total	970.419	154			

a. Predictors: (Constant), lnPC2scale, lnPC1scale

b. Dependent Variable: NormPro_4trade

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	10.847	2.079		5.218	.000
	lnPC1scale	-1.339	.397	-.268	-3.374	.001
	lnPC2scale	-.940	.434	-.172	-2.167	.032

a. Dependent Variable: NormPro_4trade

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