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International Competition in Printed Circuit Board Assembly

Keeping Pace with Technological Change

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INTERNATIONAL COMPETITION IN PRINTED CIRCUIT BOARD ASSEMBLY: KEEPING PACE WITH TECHNOLOGICAL CHANGE

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PREFACE

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PREFACE

Competition in a period of rapid technological change is the subject of this and three other companion reports.[1/] Four relatively mature industries of considerable interest to less developed countries were chosen to investigate whether organizational and technological innovations are of any relevance to them. The answer is a resounding yes. Organizational changes, automation, and use of new materials to change the production process and to transform the product itself were found to be of tremendous importance in each sector. These changes quite overwhelm simple differences in factor costs.

This research was financed by the World Bank's Research Committee, to which we are all very grateful. Numerous colleagues have supported this work and we would like specially to thank Nancy Barry, Carl Dahlman, Sandra Salmans, and Masami Shimizu. Our greatest debt is to managers and engineers in dozens of companies in six countries who spent their valuable time with us.

1/ International Trends in the Steel Mini-Mill Industry.
International Competition in the Bicycle Industry.
International Competition in the Footwear Industry.

1. INTRODUCTION

1.1 Background

Innovation is the lifeblood of the electronics industry. Diffusion of innovation proceeds at varying rates in different countries, creating differences in the productivity with which resources are used, and hence affecting the competitive position of nations. At this moment, there is a special ferment in the world of manufacturing as organizational innovations, automation, and new materials are transforming not only the manufacturing process but also, in many cases, the product itself. The speed at which these innovations are absorbed is likely to have a significant impact on a country's ability to compete. Developing countries face a special challenge as they determine how best to keep pace with the changes.

In this study, we project the effect of innovative manufacturing technologies on the long-term productivity of firms and countries. We believe that, through such analysis, we are enriching the debate on differences in international productivity, and suggesting new policy directions to improve productivity in developing countries.

For the study, we have chosen to focus on a very specific portion of the electronics industry: the assembly of printed circuit boards. This focus allows discussion to be conducted in a concrete way, using detailed unit cost numbers in different economic settings. Assembly of printed circuit boards is a major industry in a large number of very diverse countries. Technical change in this industry, therefore, has significant implications for production and trade.

1.2 Assembling the Printed Circuit Board

The Printed Circuit Board (PCB) is an internally wired, typically rectangular, substrate which holds a number of electronic components. The internal wiring is accomplished through a series of photographic processes when the PCB is manufactured. Components placed on the PCB are, therefore, connected electrically to form a circuit that performs some desired function.

Placing components on the PCB, or assembling (stuffing) the PCB, is a fundamental aspect of manufacturing a wide range of electronic products. The PCB is used in products ranging from medical instruments, videocassette recorders and handheld calculators to defense equipment. Assembling a PCB for a computer can be very similar to assembling a PCB for a television or a videocassette recorder. As a consequence, a small contract assembly industry that assembles PCBs for widely different end products has grown rapidly in recent years. However, most PCB assembly is done by manufacturers creating their own products.

Till recently a highly labor intensive activity being performed increasingly in low wage locations, PCB assembly has undergone major and rapid changes in the last decade. Electronic components placed on PCBs have changed dramatically, both physically and in their performance, assembly technology has achieved far-reaching levels of organizational sophistication and automation, and the very process of designing products has been radically altered.

Two types of PCBs predominate: through-hole, in which wiring (or "leads") from individual components pass through holes drilled in the PCB; and surface mount, in which components are soldered directly onto the board with a paste that acts as an electrical conductor. Surface Mount Technology (SMT) is emerging as the assembly technology of choice since it permits greater miniaturization and hence greater product functionality.[1]

Manual placement of components into through-hole boards had been the dominant assembly technology since the 1930s. In the early 1970s, automated placement of a wide range of components made possible vastly increased speeds (and often the quality) of placement. Today, programmed automatic insertion of components into a board is considered basic. Such automation is spreading rapidly since it economically dominates manual assembly even at low wages. SMT assembly is remarkably difficult to do without automation since very high precision is required in assembling the small components on a dense board.

The term "automation" continues to acquire new meaning. While much hype surrounds them, flexible manufacturing and "computer-integrated" manufacturing (CIM) are no longer distant fantasies: they exist in increasingly large numbers of production systems. CIM is the electronic, programmed linking and control of different workstations. The ability to program allows flexibility in changing the mix of production through small changes in software. Boards of very different sizes with very different components can be seen moving side by side on the most modern production lines.

To remain competitive, firms must make prudent technological assessments and timely technology choice decisions. Technological shifts of the type described above (the move from manual to automated insertion, or the move to SMT) require new equipment to be put in place. However, new equipment by itself has little value without appropriate organizational structures. Productivity gain requires not only appropriate assessment and acquisition of new equipment embodying new technologies but, more importantly, their implementation, organization, and continuous refinement.

A firm may generate great gains by simply reorganizing equipment, employing new materials controls strategies, and rationalizing product designs. The lesson here is that tremendous improvements can be achieved without large capital outlays to acquire new equipment.

In particular, the system of changes associated with the term "just-in-time" (JIT) must be considered a major technological innovation. Though popularly identified with inventory reduction (a worthy goal in itself), JIT goes much beyond that. Very broadly, JIT may be viewed as a systematic process of experimental learning on the shop-floor. The process of inventory reduction has led to several incremental innovations that have

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1/ Other exciting and commercially viable technologies contributing to further miniaturization are described in Appendix A.

cumulated to provide major cost reductions. Strong emphasis on worker training, team work, and flatter hierarchies has accompanied these changes.

Finally, a method known as "design for manufacture" (DFM) is set to transform the product design process with profound implications for competitiveness. DFM - in contradistinction to the traditional, sequential approach to product design, development and manufacture - focuses on coordination across several functional departments, especially design and manufacturing, so that the new product is easy to manufacture. The key principles underlying DFM are reduction in number of parts and commonality of parts across product generations, leading to quick introduction of new and enhanced products.

The best companies in the world are simultaneously applying all these principles and techniques (leaner organization with greater delegation of authority, move to greater and more integrated automation, improved design methodologies). The electronics end-product market demands such commitment. The implications of these trends for international competitiveness are the subject of this report.

1.3 Trends in International Trade

To set our discussion on international competitiveness in perspective, it is useful to consider recent trends in electronics trade. Trade in electronics products has grown in spurts. See Table 1.1.[2] After substantial growth in the 1970s, the total value of trade for most electronics products stagnated in the first half of the 1980s. Starting around 1984, new developments in microprocessor technology led to the emergence of the personal computer industry which also gave a tremendous fillip to movement of computer hardware across borders. Other electronics products also received a boost in production and trade during this period as the pace of new product development quickened. In the past few years, the fortunes of electronics products seem to have diverged. Computer trade has continued to do well, as have certain portions of the consumer electronics industry. On the other hand, trade in lower-end products (audio equipment and radio broadcast receivers) has tended to stagnate.

Japan has been the dominant exporter of electronics products through the 1980s even though, over the decade, Japan lost market share in all the broad product categories listed in Table 1.1. Market share loss in computers was the consequence of the emergence of cheap personal computers produced in Taiwan and Korea. Audio equipment and radio broadcast equipment have significant labor-intensive product segments that have been conceded to lower wage producers. Interestingly, however, since 1987, Japan has regained some of its market share in television receivers and telecommunication equipment. Both these product categories have some new and high quality products (e.g. facsimile machines) which are dominated by the Japanese.

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[2] The specific years chosen in Table 1.1 mark shifts in trends.

It is interesting to note also that the erosion of U.S. market share has come to a halt since 1987, and in a few product categories the U.S. has increased market share.

The newly industrializing economies (NIEs) have gained market share over the decade. However, most of the gains were made prior to 1987. Since 1987, they have lost market share in television receivers and telecommunication equipment, the product groups in which Japan has done well. It appears that in these product groups the NIEs are experiencing a squeeze from low wage countries at the low end of the product spectrum and from Japan and, to some extent, the United States which are producing new and innovative products.

Table 1.1: TRADE IN ELECTRONICS PRODUCTS

ACCOUNTING MACHINES & COMPUTERS (SITC 7142)

	1981	1984	1987	1988	1989
Total Value of World Trade (US$ billion)	1.63	1.63	2.11	2.31	4.00
			Market Share (%)		
Japan	55.22	61.87	43.65	36.97	30.45
USA	9.23	7.91	4.95	5.13	6.07
Germany, FR	4.44	3.36	5.04	4.56	4.10
Taiwan	5.92	7.56	16.76	19.76	16.86
Korea, RP	1.65	1.77	2.39	1.85	3.17
Singapore	3.95	2.28	2.61	3.21	5.58
Hong Kong	3.80	4.23	7.97	7.83	8.26
Malaysia	0.04	0.01	0.05	0.10	1.95
China	0.05	0.45	4.21	6.86	5.64
Mexico	0.30	0.32	0.11	0.06	3.40
TOTAL of the above 10 countries	84.60	89.76	87.74	86.43	85.48

RADIO BROADCAST RECEIVERS (SITC 7242)

	1981	1984	1987	1988	1989
Total Value of World Trade (US$ billion)	6.22	6.64	10.98	12.23	11.87
			Market Share (%)		
Japan	44.38	37.96	33.36	31.23	19.00
USA	2.85	4.76	2.06	3.00	2.98
Germany, FR	4.24	3.16	3.36	2.61	2.66
Taiwan	10.58	9.32	8.19	7.08	7.06
Korea, RP	0.56	0.60	0.99	0.63	0.74
Singapore	7.03	7.25	5.79	6.79	8.99
Hong Kong	10.05	8.73	6.02	4.46	4.72
Malaysia	1.22	2.04	4.58	6.56	9.76
China	0.70	2.14	7.05	9.24	16.45
Mexico	0.20	4.12	5.52	7.62	6.35
TOTAL of the above 10 countries	81.81	80.08	76.92	79.22	78.71

AUDIO RECORDERS (SITC 8911)

	1981	1984	1987	1988	1989
Total Value of World Trade (US$ billion)	8.42	11.10	17.32	16.72	16.86
			Market Share (%)		
Japan	74.63	77.61	62.81	58.03	55.26
USA	3.91	1.70	1.56	1.78	2.47
Germany, FR	3.37	4.42	6.77	4.20	3.31
Taiwan	2.35	2.47	4.55	5.40	4.45
Korea, RP	2.06	1.65	7.79	10.68	9.45
Singapore	1.14	1.48	2.02	3.88	3.25
Hong Kong	1.47	1.40	2.11	1.75	1.94
Malaysia	0.08	0.16	0.49	1.44	2.88
China	0.12	0.39	0.95	2.74	4.72
Mexico	0.55	0.32	0.26	0.32	0.75
TOTAL of the above 10 countries	89.68	91.60	89.31	90.22	88.28

<u>Table 1.1</u>: Contd.

TELEVISION RECEIVERS (SITC 7241)

	1981	1984	1987	1988	1989
Total Value of World Trade (US$ billion)	4.95	4.50	7.50	10.54	12.66
		Market Share (%)			
Japan	29.78	28.66	16.04	19.11	19.33
USA	5.00	3.42	2.87	2.70	3.49
Germany, FR	16.01	12.36	11.45	13.31	12.32
Taiwan	9.67	8.71	8.32	5.47	4.96
Korea, RP	8.07	12.84	11.29	10.79	8.22
Singapore	5.01	4.4	4.38	4.43	4.88
Hong Kong	0.72	1.49	2.56	2.54	2.38
Malaysia	0.07	1.63	4.22	3.07	3.62
China	0.15	0.25	2.76	3.28	3.95
Mexico	0.32	1.94	4.17	5.40	7.13
TOTAL of the above 10 countries	74.80	75.70	68.06	70.10	70.28

TELECOMMUNICATIONS EQUIPMENT, NES* (SITC 7249)

	1981	1984	1987	1988	1989
Total Value of World Trade (US$ billion)	17.00	19.80	29.72	35.48	40.74
		Market Share (%)			
Japan	27.60	32.43	32.48	32.12	33.04
USA	16.07	14.57	11.41	10.17	11.77
Germany, FR	10.31	7.01	8.45	7.88	6.18
Taiwan	5.14	6.50	6.81	6.43	5.09
Korea, RP	1.60	2.59	4.50	4.33	3.61
Singapore	2.17	2.27	2.38	2.82	2.33
Hong Kong	0.88	2.24	1.90	2.29	3.06
Malaysia	0.76	0.86	1.01	1.36	1.82
China	0.12	0.23	1.05	1.56	2.30
Mexico	4.51	4.40	2.83	2.78	2.60
TOTAL of the above 10 countries	69.16	73.10	72.82	71.74	71.80

Source: UN <u>Comtrade Database</u>, Geneva

At the low end of the product range, China has emerged as the most substantial new player on international markets. To a smaller extent, Mexico has gained market share. Remarkably, the Chinese increase in market share has occurred across all five product categories. It is not surprising that China has done best in audio recorders and radio broadcast receivers, the two products at the bottom of the technology hierarchy.

A closer look at the more dynamic and higher value-added products demonstrates the importance of recent technological trends to the competitiveness of high-wage, industrialized countries. New innovative products imported into the U.S. come entirely from Japan (see Table 1.2 for Japanese share in U.S. imports of facsimile machines; similarly, electronic notebooks are virtually a Japanese monopoly). Consider video cassette recorders (VCRs), which have a longer history than facsimile machines. The

United States imports over 70 percent from Japan, with Korea a distant second. China (or Hong Kong) have virtually no sales of VCRs to the U.S. Similarly, the United States continues to buy computers from the traditional sources: Japan, Korea, and Taiwan.

Table 1.2: US IMPORTS OF SELECTED ELECTRONICS PRODUCTS

	FAX	VCRs	CAMCORDERS	TWO in ONE	TV 1	TV 2	COMPUTER	DISPLAY UNIT	DOT MATRIX PRINTER
Total Imports	776.56	2291.52	1080.70	607.47	417.92	445.57	1910.77	1715.63	905.60
				Market Share (%)					
Japan	91.64%	71.95%	97.74%	16.28%	0.19%	0.68%	12.14%	32.49%	85.28%
Taiwan	0.30%	1.17%	0.00%	12.68%	13.97%	5.92%	25.64%	30.10%	0.99%
Korea	3.46%	14.59%	1.54%	10.32%	9.67%	3.91%	10.45%	30.11%	0.64%
Singapore	0.37%	0.38%	0.19%	13.38%	8.99%	6.75%	13.17%	2.28%	8.61%
Hong Kong	0.05%	0.03%	0.09%	1.13%	1.09%	0.10%	8.10%	0.25%	0.23%
Malaysia	0.00%	3.29%	0.03%	19.47%	21.08%	5.84%	0.00%	0.00%	0.00%
China	0.00%	0.03%	0.00%	22.99%	5.09%	0.24%	0.00%	0.00%	0.00%
Mexico	0.00%	0.00%	0.00%	0.10%	34.23%	73.50%	7.59%	0.87%	0.94%
				Unit Value					
Japan	514.19	220.91	529.44	44.58	156.60	273.91	8281.25	507.67	181.58
Taiwan	180.38	172.14	-	38.67	143.77	178.22	441.03	249.99	356.92
Korea	295.31	163.13	476.86	57.17	137.52	169.21	545.57	191.04	115.72
Singapore	475.50	214.98	693.00	45.87	147.40	176.80	471.12	236.93	430.91
Hong Kong	-	258.33	945.00	23.63	122.57	455.00	385.00	436.40	523.75
Malaysia	-	176.96	284.00	25.84	126.39	189.93	-	-	-
China	-	186.00	-	126.40	135.37	154.00	-	-	-
Mexico	-	-	-	126.40	139.01	162.78	1278.67	225.15	2829.00

Note: TV 1 = 33 - 35 cm
TV 2 = 45 - 50 cm
Two in One = Radio-tape combination incapable of recording
Source: Electronics Foreign Trade, Electronics Association Industries: Washington, D.C., March 1991.

Importantly also, the U.S. electronics industry has undergone a revival.[3] In the past four years (i.e., from 1986 to 1990) exports have grown faster than imports. In 1990, imports were flat while exports rose by almost 12 percent, reducing the electronics trade deficit from $13 billion to $6 billion. Export growth has occurred in all the broad categories of electronics products (consumer, industrial, communications, and parts). Household audio and video equipment, traditionally the most vulnerable segments of the U.S. electronics industry, has experienced increasing production and exports, while imports have actually declined in the past few years.[4]

3/ The discussion on trends in U.S. production and trade is based mainly on Electronics Market Data Book and other publications of the Electronic Industries Association, Washington D.C.

4/ U.S. Department of Commerce. 1991. U.S. Industrial Outlook. U.S. Government Printing Office, Washington D.C. pp. 38-2 and 38-12. Foreign producers have been responsible for a substantial portion of increased U.S. production; however, the point really is that in a high-wage country like the U.S. at least a small range of consumer electronics goods can be produced competitively when appropriate management practices and technologies are used.

Increased U.S. competitiveness in international markets is partly due to the depreciation of the U.S. dollar. However, as we shall show in this report, a wide range of U.S. producers have in the past lacked international competitiveness because they have not kept pace with best practice in design and production technology. We will provide examples of firms that have raised their efficiency levels to international best practice in recent years through conscientious investment in human and organizational development. It is the efforts of these firms that show up in improved U.S. trade performance.

1.4 Scope of the Study

Being internationally competitive takes a lot of doing: materials must be procured efficiently from domestic and overseas sources, production must be organized efficiently and staff motivated appropriately, links with buyers and distributors must be maintained to obtain timely information on trends in demand, and so on. We are in no position to analyze the entire chain of activities. Our focus is on the manufacturing process (See Figure 1.1).

There can be little doubt that efficiency in manufacturing will be a key ingredient of success at least for the less developed and newly industrializing countries. It is our conjecture, moreover, that certain underlying principles of manufacturing (efficient management and good flow of information) hold equally for other components of the value chain.

A related boundary on the quantitative exercise is our focus on production costs. We have emphasized above that competition is multi-faceted and depends on the firm's ability to respond flexibly to customer needs, implying that low costs are not the only factor determining competitive ability. We have been able to quantify costs in very great detail, as will become evident in the following chapters. However, quantifying the benefits of flexibility and superior product characteristics is much more difficult. This is unfortunate since many of the more innovative processes we study lead primarily to gains in flexibility and product enhancement. Our approach has been to discuss quality and flexibility with ordinal measures and, more importantly, to discuss the trade-offs between product characteristics, flexibility, and cost. For example, when a process leads to an obvious improvement in product characteristics but limited increase in production cost, then it is relatively safe to conclude that the process is likely to diffuse widely.

1.5 Country Stylizations

It is a long-held principle among economists that systematic differences in operational efficiency across countries cannot persist over long periods of time. Any such differences, according to the conventional wisdom, would soon be wiped out by economics' invisible hand. Leamer 1984, for example, says that unless there exist "biological differences" between the nationals of different countries, or "effective counterintelligence agents," all economies should be equally efficient in the tasks they perform.

Like other researchers, however, we have observed empirically that this mind set does not correspond to reality. In this sector and others, we find that some of the newly-industrializing economies operate at a consistently higher level of efficiency than other country types. They invest more effectively, learn faster, and stabilize their production at higher levels of efficiency.

It would be pointless to dismiss such differences as illusory. Indeed, we strongly believe that, by examining their causes, we can enrich the debate on international productivity differences.

In this and companion studies, the firm has emerged as a dynamic organization, even in those industries previously thought to be mature. The successful firm is in a constant state of flux as it introduces and absorbs technical and, above all, organizational innovation: automation in design and manufacture, design for manufacture, quality control and inventory management.

For the firm, then, the learning curve is extremely steep - but so is the reward. In fact, it is probably safe to say that the firm's position on the learning curve is more critical to its success than other, exogenous factors. Firms - notably LDC manufacturers - that are only at the beginning of the curve are substantially less efficient than those at the end, and not even cheap labor - as in the case of LDCs - can make up the differences.

Accordingly, we set ourselves the task of accounting for efficiency differences in terms of operational characteristics, and then discussing how performance, as defined by those characteristics, could be improved. We do not trace the learning curve, or limit our analysis to the beginning and end. Rather, we observe the process at several points in time - almost like snapshots - and discuss, in a qualitative way, how to advance from one to the next.

In our quantitative exercises, therefore, we introduce important stylizations regarding the level of efficiency attained. Of the three groups of countries we study, we assume the newly-industrializing economies (NIEs) to be the most efficient. These were represented in our study by South Korea and Singapore. Although our interviews in Japan provided us with substantial information on the frontiers of production technology, the benchmark cost estimates for developed countries (DCs) are based on conditions in the United States. Less-developed countries (LDCs) are represented by Mexico and Indonesia. After demonstrating the impact of inefficiencies, we examine cost differentials across groups if they all operated at the NIE level of efficiency. That comparison allows us to study the effect of factor costs--the costs of labor, land and capital--and technology choices.

1.6 Plan of the Study

Product and manufacturing strategies of the sample of firms visited for this project are described in the next chapter. On the basis of these visits, the manufacturing literature, and our engineering knowledge and experience, we created benchmark factory cost models defined at a fine level of specification (Chapter 3). These benchmark models are intended to replicate production costs of a "representative" factory in the countries visited. A series of cost scenarios based on the adoption of modern management practices and new hardware technologies are examined in Chapters 4 through 6. Throughout, the lessons from our cost models are illustrated with concrete case studies based on our field visits and the industry literature.

The concluding chapter comments on the shifts occurring in the competitive abilities of different country types.

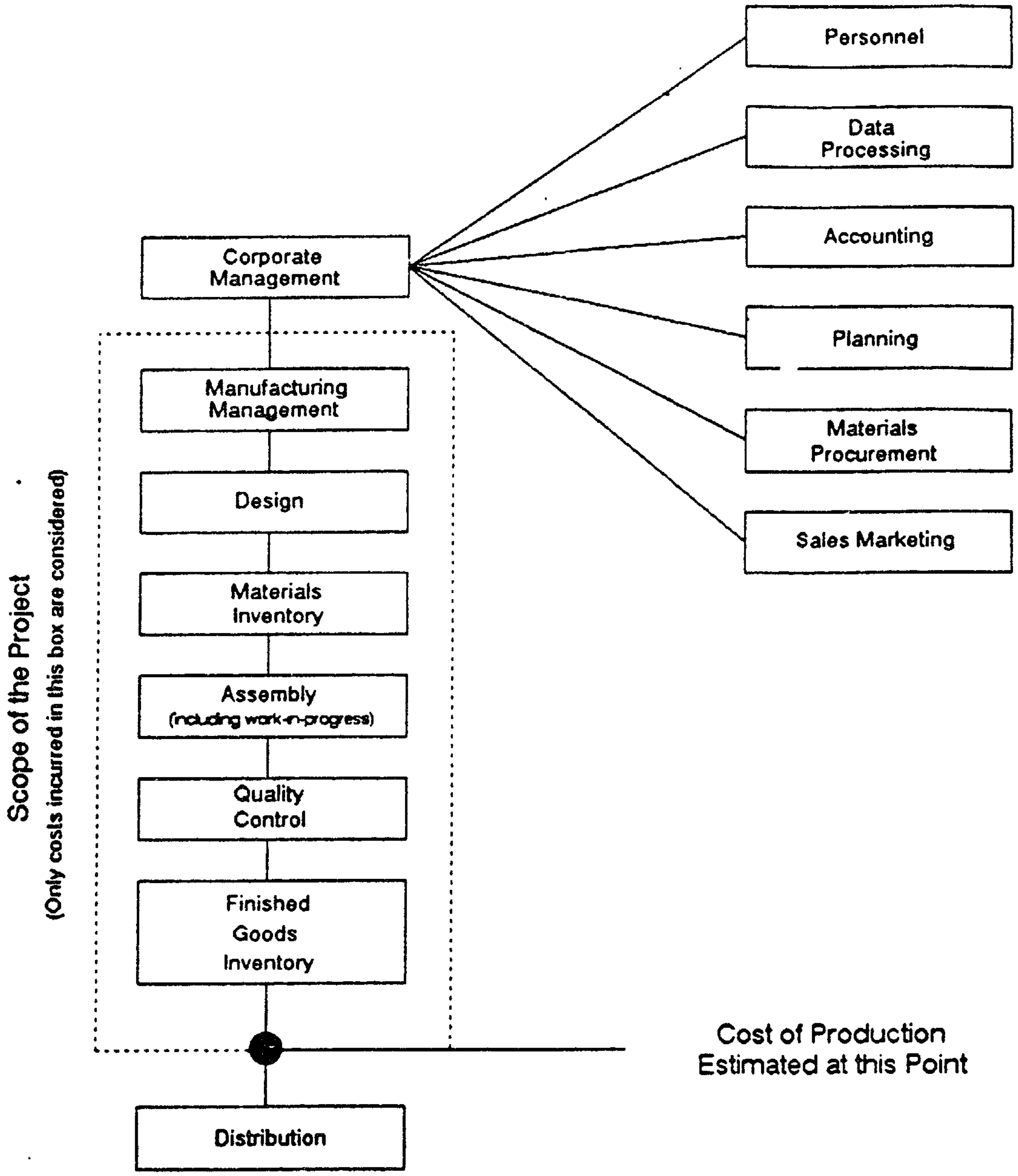
Personnel
Data Processing
Accounting
Planning
Materials Procurement
Sales Marketing
Corporate Management
Manufacturing Management
Design
Materials Inventory
Assembly (including work-in-progress)
Quality Control
Finished Goods Inventory
Distribution
Scope of the Project
(Only costs incurred in this box are considered)
Cost of Production Estimated at this Point

Figure 1.1

2. THREE MANUFACTURERS: A STUDY IN CONTRASTS

2.1 Objectives

In the following chapters, we will simulate changes in unit costs when alternative techniques are adopted by stylized, country-specific benchmark factories. The discussion here provides some of the basis for stylizations discussed later in the report. We summarize first the basic pattern of technology adoption by companies visited for this project and then discuss in some detail three companies, each representing one of the three country types. The objective is to relate the choice of production technique to the company's economic environment, product strategy, and human resource strategy.

Nine PCB assemblers in six countries were studied in considerable depth, usually over a day, with some follow-up questions and visits. In addition, similar interviews were conducted with 33 other firms (in the bicycle, shoe, and steel industries), and the stylizations presented here conform with the general results of the project.

The manufacturers we visited were chosen for their representativeness of one of the three country types. Extensive consultation with industry and country experts, review of the industry literature, and our industrial consulting experience was the basis for choosing particular firms. The visits were not intended to generate primary data on the basic manufacturing process; that was derived from our experience and expertise. The visits were intended, instead, to enhance our grasp of the range of manufacturing competence. Within a country type, factories in the four industries resembled each other more closely in terms of key operational characteristics than did factories in the same industry across country types. Thus, the relatively modest number of visits to manufacturers in each sector was effectively amplified by visits to manufacturers in other sectors.

2.2 Technology Usage Summary

Before examining in detail three firms (one from each country type) that assemble PCBs, let us summarize the technologies in use at the electronics companies visited. See Table 2.1 below. Note that all firms employing automated technologies also have some manual insertion, since most PCBs require some manual assembly for attachment of large and odd parts. All the DC firms use or have some experience with surface-mount technology, all NIE firms use automated through-hole, and none of the LDC firms uses any automated technologies. One NIE firm is an advanced user of SMT. Based on our sample, a clear technological progress from manual to automated through-hole to SMT can be seen. This is not surprising since effective use of each higher level of PCB assembly technology requires that the lower technologies be mastered.[1]

Table 2.1: TECHNOLOGY USAGE SUMMARY

	COMPANIES								
	DC			NIE				LDC	
Technology/ Practice	U.S. A	Japan B	U.S. C	Singapore D	Korea E	Korea F	Korea G	Mexico H	Indonesia I
SMT	•	•	*	•	o	o	o		
Auto thru-hole	•	•	•	•	•	•	•		
Manual thru-hole	*	*	*	*	•	•	•	•	•
Just-in-time	o	•	o	o	*	*	*		
MRP	•		•	•	•	•	•		
Design for manufacture	o	o			*	o	o		

LEGEND

- • Technology or practice is firmly established.
- * Limited usage.
- o Being considered.

SMT = Surface Mount Technology
MRP = Materials Requirements Planning

In other respects that may be more critical to final unit cost, however, the U.S firms lagged the NIE manufacturers. The NIE firms and the two U.S. firms had implemented Materials Requirement Planning (MRP) as a material ordering, and job scheduling system. However, it was evident that the NIE firms had made greater progress towards conceptualizing and implementing some of the features of just-in-time (JIT).

We shall discuss below that consciousness of product quality assurance programs has risen greatly in the United States and formal procedures are being instituted widely in electronics and other industries. However, our observation is consistent with that of others who also find NIEs to have taken the lead over some DCs in shop-floor planning and reduction of waste (see Womack and associates 1991).

1/ Even in LDCs, firms with close foreign links (joint ventures or foreign subsidiaries) tend increasingly to have automated through-hole assembly. Our "scenarios" in Chapter 4 clearly indicate that such use of automation is indeed economical even at very low wages. Lack of widespread use of automation in LDCs can be attributed to limited skills in operating and maintaining the more advanced equipment. We discuss at length in following chapters the importance of shop-floor procedures for minimizing waste. When such procedures are not in place, automation can do more harm than good.

As noted in the introduction, JIT is not merely an inventory reduction method but is also an institutionalization of continuous learning through incremental changes. Unlike MRP, which serves as a high-level database and provides overall materials management function, JIT emphasizes shop-floor practices. At the same time, JIT is a tool for the systematic elimination of waste in all aspects of manufacturing. It is clear both through the factory visits and through our consulting experience that the NIE firms have progressed beyond U.S. firms in this regard. This is reflected, as will be discussed in the next chapter, in indicators such as lower scrap, shorter cycle times, and greater machine reliability at the NIE factories when compared with the U.S. factories.

2.3 Developed Country Firm: Company A

Company A is a large manufacturer of telephone equipment and supplies headquartered in the United States but with many plants around the world. The U.S. factory we visited makes small telephone exchanges and has over 300 employees involved in design, manufacture and support functions. The factory itself is about 20 years old, and produces for very competitive domestic and international markets.

This showcase factory has the company's first substantial implementation of SMT. It took factory managers three years to overcome the vagaries of the technology, but they have done so successfully and now advise other factories in the company about SMT. They were clearly on the forefront of U.S. SMT usage. They state that use of automation requires improved materials flows and higher quality materials. They needed to have these capabilities in place before fully implementing SMT.

Their assembly lines boast high levels of automated SMT insertion equipment, automated through-hole technology, and computer-supported manual assembly. Manual assembly stations have television screens with multi-color diagrams showing the assemblers where to insert the next part. The one-shift operation produces a wide variety of PCBs, often in lots of about 25 units.

JIT is a new concept to this company, and to the factory in particular. It has traditionally been MRP-driven, using highly systematized practices for parts procurement and inventory control. Recently, management has tried to integrate JIT purchasing and management techniques into existing procedures, but recognize they have a long way to go.

The factory formerly had a quality review department that tested products after they passed through major assembly stations. Now this group has been disbanded. In its place, the factory has implemented automated inspection capabilities in the insertion machines, giving real-time feedback on process quality.

Factory management has made great efforts to cut inventory levels, reducing inventory by 80 percent in just three years. The factory leads the company in inventory reduction.

Company A has chosen to site this factory in the U.S. rather than overseas because they want to be closer to many of their largest customers and their own design staff. The company also states that the low labor content in their products (due to heavy automation) reduces the incentive to go abroad for cheaper labor.

Our scenarios indicate that full achievement of JIT would reduce PCB assembly costs for this factory, but not enough to compete solely on a cost basis with NIE firms. Also, direct labor wage cuts would have little impact. However, the design-for-manufacture (DFM) scenario showed great potential for drastic cuts in product cost. This, coupled with increased speed of product development, lowers the cost of product differentiation. As a result, DC firms as long as they stay one step ahead of NIE manufacturers can have a comparative advantage.

2.4 Newly Industrializing Economy Firms: Company E

Company E is a highly diversified Korean manufacturer of consumer electronics products. Generally between 65 and 90 percent of each type of its products are exported. Often, one-third of the production goes to the U.S. The company is quite concerned about import restrictions in its major markets, exchange rate fluctuations, and the rising cost of labor. Company E faces both Korean and international manufacturers in both their domestic and international markets.

We visited four distinct electronics factories of this manufacturer, located within one industrial complex. Typically, they used high levels of automated through-hole insertion, which in some cases was supported by automated board loading. Recently they have increased to approximately 50 percent the proportion of parts inserted into the board automatically.

While they have tested SMT processes in their factory automation research laboratories, they have not implemented SMT for production of their consumer goods - nor do they plan to in the near future. This is particularly interesting because another division of this company produces very simple SMT components for sale internationally. Nonetheless, they note that "everything gets smaller" and that, in time, SMT usage will probably predominate since it is the "way of the future."

They also used manual insertion for attachment of parts not easily inserted automatically. The manual work stations were not computer-supported. Instead, workers used color-coded assembly drawings as a guide.

More than 1,500 people were employed on the shop floor of the factory producing color television sets. They work one shift of 10 to 11 hours a day, six days a week. Workers are housed in company dormitories nearby.

The manufacturing process has been very closely analyzed, and individual manufacturing activities are quite efficient. In-process inventories are low, even though the firm does not claim to use JIT manufacturing practices. Assembly lines are dedicated to the manufacture of similar products in a product family. The assembly line is very flexible, in that it is easily changed over to produce a different product within the product family.

Company E's products are commodity consumer goods. They do not manufacture the flashiest products embodying the newest technologies. Their aim is to keep unit costs low and minimize development costs by producing very large volumes of basic consumer electronics products.

Company E managers say they want to work hard to greatly improve quality, which is generally already at high levels for most of their products. They hope to achieve this through tighter inspection of key incoming components and tighter quality requirements for in-process inspection.

Company E states that their most important challenge is product redesign, by means of which they hope to cut dramatically the price of their products. For example, they envision a major change in a particular PCB for a videocassette recorder that may raise the price of a key component, but reduce the total cost of the board while increasing its quality.

To compensate for rising labor costs, Company E hopes to purchase lower-cost components, produce more components internally, and automate more.

2.5. Less Developed Country Firm: Company H

Company H is a small Mexican manufacturer of stereo systems and radios. They produce only for domestic sales, and in particular for low-end markets. They compete almost exclusively on price, not quality. Many of their product designs are reverse-engineered versions of foreign products. Increased competition since the opening up of the Mexican market has not yet led to greater production efficiency. Instead, the company is diversifying away from electronics. This is occurring at a time when foreign managed electronics assembly operations in the maquiladora areas of Mexico are experiencing substantial growth (see Appendix B).

Company H used personal computers for accounting and purchasing. There was little evidence of any systematic manufacturing planning and control. Raw materials, work-in-process and finished goods inventories were all high. Company H tries to keep finished goods inventories to less than six weeks, due to the high cost of capital.

The assemblers worked at large, plain wooden tables. The PCBs they assembled were simple and small, none larger than 4 by 6 inches. To keep labor content high, and so keep materials expenditures low (and in the past, to guarantee availability), the company manufactured many of the electronic components and other parts used in their products. We observed that they wire-wound their own inductors and transformers, and stamped their own speaker cones. Product quality was low, and inspection occurred only at the end of the assembly line. Many units were being reworked; some of them had been returned by retailers.

The factory employs one shift, six days a week. The firm now has about sixty employees, down from 100 a year earlier. The company wants to avoid large-scale layoffs.

The firm is facing a very difficult competitive situation. Typically, they have had great difficulty in getting components. When available, these components were often of very poor quality, delivered late and in inadequate volumes. Since Mexico's entry into GATT and the related lowering of import barriers, some higher-quality imported components have become available - but so have imported end-products that are both much higher in quality and lower in price. The new competitors include Japan, Korea, Taiwan, the United States and Germany. Company H also sees China as a threat.

Management sees a declining market for low-end stereos. This, coupled with new foreign competition, leaves them searching for a profitable activity. In the short run, Company H is undecided over its future action.

To maintain and bolster sales, the company is entering into a joint venture with a Japanese television manufacturer. Initially, Company H will act only as a distributor of the low-end television sets but, in time, it will do all final assembly, using parts provided by the Japanese company. At that point, Company H hopes to develop a consortium of Mexican manufacturers, each of which would manufacture and assemble particular parts and subassemblies.

At the same time, they are increasingly moving to manual manufacture of quality wooden furniture (coffee tables, shelves, cabinets), a product with very high labor content. They had carpentry skills because they manufacture cabinets to house their stereo systems.

Company H also faces an image problem. They state that Mexican consumers believe that domestically-made electronics products are of inferior quality. On the other hand, Mexican consumers believe Mexican furniture is of high quality. Company H has even considered changing its brand name so that it may sound Oriental.

Our scenarios show that Company H could benefit greatly from higher-quality products and reduced inventories. These could be achieved through such means as improved manufacturing planning and control, worker training, higher-quality raw materials and continuous inspection. Once Company H has its processes under control, it could compete with NIE firms currently producing lower-cost products.

3. FOUR BENCHMARK FACTORIES

3.1 Background

To analyze the impact of innovation on the electronics industry, it is necessary to move from real-world case studies to stylized representations (benchmark models) of manufacturing operational parameters and input costs in each country type. It is only by doing so that we can introduce controls, eliminate extraneous variables and thus analyze the impact of change.

A benchmark factory for a particular product in a given country is intended to represent a prototypical firm manufacturing that type of product in the country. Thus, a benchmark model does not represent any particular firm. The purpose of the benchmark models is twofold: to replicate the relative ranking of LDCs, NIEs, and DCs in terms of unit costs, and then to use as the basis for simulating the effect on firms of the new technologies.

It is useful to clarify the relationship between a "benchmark" factory and "optimal" technique of production. Since input costs vary in the three country types, we would expect that techniques of production most commonly in use reflect those differences. Our benchmarks show that the technique in use does, in general, vary by country type. DC techniques, in particular, are significantly different from techniques in the other country types (except in the case of shoes, where the benchmark factory even in the DC is assumed to have the same technique as in the other two country types). The difference between LDC and NIE benchmarks is smaller. In the present report, we have two benchmarks for the NIE, one embodying the same technique as in the LDC and the other embodying a more advanced technique.

The benchmark factories in the three country types are assumed here to assemble the same PCB. This is necessary for making international cost comparisons. We have chosen a PCB that is of medium size and complexity; such a PCB may be found in a minicomputer, but it may also be found in the more advanced personal computers and televisions. Thus, in keeping with the generic use of PCBs, we do not identify the benchmark PCB with a specific final product. To study the significance of board complexity, in Chapter 4 we also do cost calculations for a simpler PCB, such as may be found in low-end stereophonic equipment.

Finally, we assume that firms in all countries can access material inputs at the same price, thus focussing our spotlight on the manufacturing process.

3.2 Manufacturing Process

The through-hole PCB assembly process may be thought of as a straight line process with workstations along the line for component insertion, soldering, and testing. Typically, a set of similar components is inserted at each workstation. In the vast majority of cases, individual components are inserted one at a time.

Once inserted, the component leads are clinched (bent slightly to grip the board), trimmed and soldered. Soldering may take place after all components are inserted or after each individual component is placed. Manual soldering is a simple step employing a soldering iron and solder wire. An automated soldering process called wave-soldering may also be used: the board "stuffed" with components is passed over a bath of solder in a controlled atmosphere.

Test and rework requirements create loops in what is otherwise a linear process. Repair stations are adjacent to but not directly on the assembly line. Defective boards are routed to the repair station and then looped back into the assembly line. Every plant usually develops its own rules on the maximum number of times a defective subassembly can be looped back into the main assembly line. Though careful testing is essential for producing high reliability products, the so-called "test and repair" loops can become tremendously convoluted if a careful overview is not maintained, leading to a loss in control over production and creating an additional source of defects. Work-in-progress also increases with time spent in the loops.

Testing can be an elaborate process using specialized equipment and highly skilled labor. The standards of testing have risen rapidly over time as end-user expectations and competition in the industry have increased. For products such as medical instruments, engineering work stations or private branch exchanges (PBXs), the testing process can take longer and incur more expense than all the other production steps combined.

Arriving at the right testing strategy involves many trade-offs. The firm aims to minimize testing costs while meeting a specific quality goal. If a firm desires higher quality, testing costs are also likely to be high. Often, firms do not aim to achieve "perfect" quality and are content with some acceptable level. However, the decision-making process is not always well-informed: many firms just do not have the skills to do such testing evaluation.

There are a variety of tests. The board may be <u>visually tested</u>, i.e., a worker inspects the board to see if components are correctly located and inserted, checks the quality of soldering and looks for other errors or omissions. An <u>electrical test</u> requires use of oscilloscopes or electrical meters to check the electrical response of the circuit. <u>Functional tests</u> place the circuit board into the actual unit in which the board will operate, to investigate whether the whole system works. <u>Specialized testing units</u>, called "bed of nails" testers, may be employed to perform electrical and functional tests customized to the specific board; such custom testing is expensive. "<u>Burn-in</u>" tests require operation of the product for a specified length of time. The objective is to screen out products that do not fully meet specifications during or at the end of the testing period. The phenomenon where products work initially but fail during burn-in is referred to as infant mortality. Some products are subjected to <u>environmental testing</u>. They are placed in humidity-and temperature-controlled chambers where continuous cycling of these environmental parameters tests the boards' ability to survive at the limits of their environmental specification.

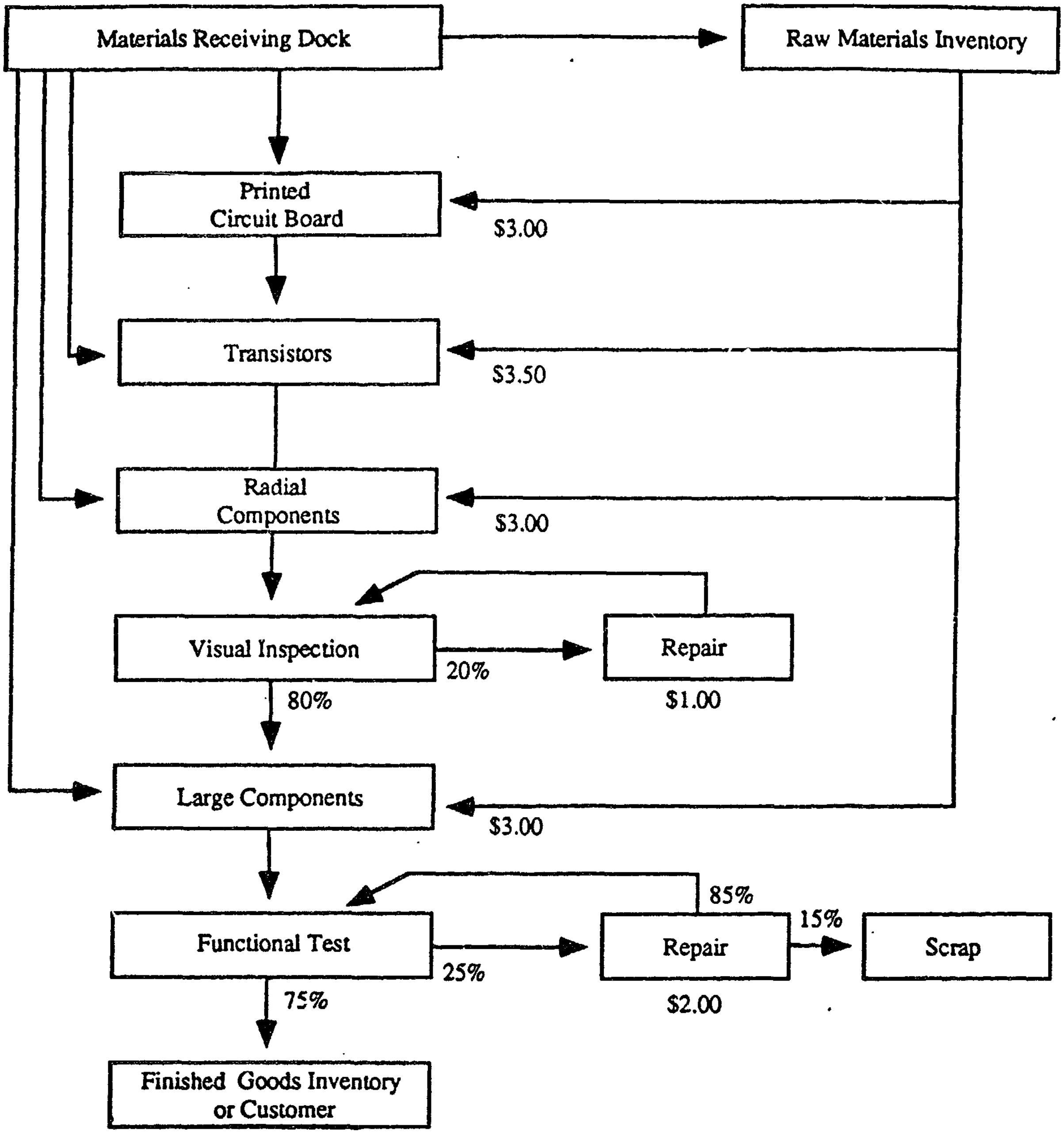

Figure 3.1: AN ILLUSTRATIVE ASSEMBLY LINE

A simple, illustrative assembly line (not the benchmark factory discussed in Section 3.4) is shown in Figure 3.1. Materials received can be fed directly from the dock to the assembly line (as would be the case in a perfect just-in-time process) or, more typically, are sent to a warehouse from which they are requisitioned when needed. The value of components added to the subassembly at each point is noted. The costs of work-in-progress rise with the number of test loops, the operation test times, and the proportion of subassemblies tested. The modern approach is, therefore, to test the subassembly as it is being assembled, rather than taking the subassembly out of linear flow process into a loop for test and repair. For such an approach to be successful, the quality of inputs must be high, work procedures must be laid out clearly, and the workers must be trained not only to perform their insertion tasks but also to be quality inspectors.

3.3 The Benchmark Factories: Physical Indicators

The parameters used are inputs to ManuCost, a software package that models manufacturing costs. ManuCost estimates work-in-progress (WIP) and value of scrap to arrive at total costs. Figure 3.2 is a schematic diagram of the cost model.

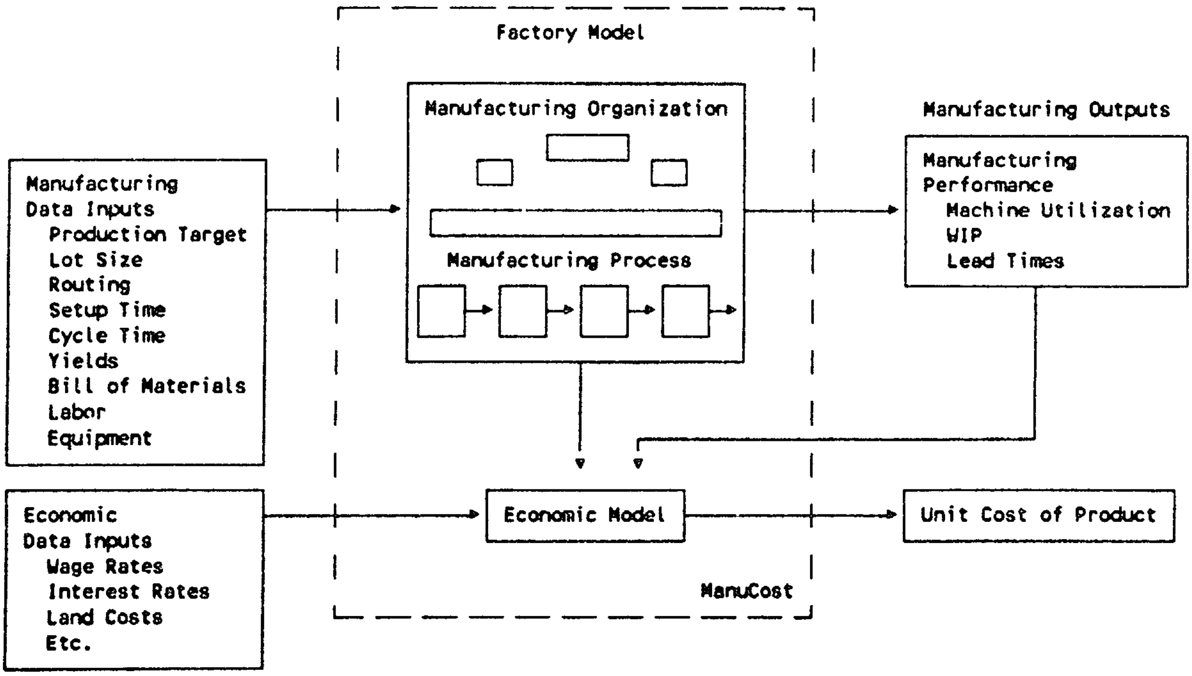

Figure 3.2 SCHEMATIC OF THE COST MODEL

The key element of the ManuCost approach is that production is modeled as a dynamic process that occurs over a period of time. This provides the basis for the work-in-process (WIP) cost category, which does not exist in aggregative models that rely only on measures such as capital-output ratio. The physical performance characteristics of machines and labor, along with a specification of how materials move from one stage to another, create the basis for quantifying waste in the system. This model structure also enables us to evaluate savings (or cost increases) that accrue when the process is simplified or a technological change, such as a more highly automated piece of equipment, is introduced into the process. See Appendix C for more details on ManuCost.

We have developed four benchmarks for PCB assembly factories: one each for the LDC and DC, two for the NIE. Table 3.1 specifies annual production in each benchmark factory and also the input requirements for meeting that production level. The table also specifies operational parameters, such as cycle time (the time taken for a PCB to be assembled), machine reliability, and process yields (proportion of boards not requiring rework). Differences in these operational characteristics determine the differences in the level of efficiency.

The prototypical technique in the LDC is through-hole manual assembly and in the NIE a transition is occurring from through-hole manual to automated assembly. In the DC, through-hole automated assembly is the dominant technique. SMT is replacing through-hole assembly in DCs at a very rapid rate and is also diffusing in NIEs; we discuss SMT in Chapter 6. The level of automation assumed here is modest. Specific operations, such as inserting and soldering, are automated, but such automation is primarily a mechanism for reducing labor. Production is still assumed to flow manually from one workstation to another. Increasingly, however, computers are controlling production flow, affecting work-in-progress more than labor input. In Chapter 6, we will discuss more advanced levels of automation in the context of SMT assembly.

In addition to differences in techniques used, firms vary systematically in the efficiency with which they use their resources. Several features of Table 3.1 are noteworthy. The LDC factory is significantly less efficient than its NIE counterpart in the use of capital and labor. The LDC Manual factory produces 25 percent less output than the NIE Manual factory, but uses more capital equipment and also more labor. NIE firms use less equipment because their machines are more reliable, work faster (smaller cycle times), and are repaired faster.

There are other sources of inefficiency in the LDC plant. Slack work methods and inadequate attention to testing lead to greater wastage of material. Higher scrap, longer cycle times, lower machine reliability and larger buffers, lead to greater work-in-progress and hence further increase the use of capital, an LDC's most expensive resource. Higher raw material and finished goods inventory in LDCs similarly increase capital use.

An indicator of organizational slack is the size of each batch of PCBs processed, also referred to as the lot size. We have taken the benchmark lot size in the LDC factory to be twice the size in the other factories. Large lot sizes are desirable when a factory has expensive machines that take a long time to be set up for a new product batch. However, in the benchmark factories described, set up times are not long; particularly for manual technologies, there is no good reason for large lot sizes. In fact, a virtue of manual processing is the flexibility it affords. Hence an efficient manual process would typically run very small lot sizes. The large lot size in the LDC manual factory reflects the uncoordinated manner in which inputs and subassemblies travel through the factory. As a consequence, many unfinished boards are processed at the same time, not because that is desirable but because production planning and scheduling are poor. This leads to the build-up of inventory and often also causes errors in assembly (See Box 3.1).

Table 3.1: MANUFACTURING PARAMETERS FOR BENCHMARK MODELS

Parameter	LDC Manual	NIE Manual	NIE Automated	DC Automated
Operating Schedule				
Days per year	240	288	288	240
Hours per day	9	8	8	7.5
Staffing--Total	46	41	29	35
Span of control a/	7	10	10	7
No. direct labor	36	33	22	26
No. indirect labor	10	8	7	9
Absentee rate	3%	0.5%	0.5%	2%
No. of machines b/	37	34	24	29
Equipment value c/				
Total value ($000)	22	20	1,484	1,846
Annualized ($000)	12	10	519	609
Sample reliability d/	25/7	40/2	40/2	30/6
Insertion cycle time (minutes)	16	14	2	2
Material inputs ($/PCB)				
PWB	12	12	12	12
DIPS	14	14	14	14
Radials	12	12	12	12
Large components	12	12	12	12
Sample yields				
Intermediate inspection	77%	80%	82%	79%
Final inspection	69%	74%	85%	61%
Lot size	50	24	24	24
Inventory (months) e/				
Raw materials	2.5	1.0	1.0	1.5
Finished goods	1.0	0.33	0.33	0.5
Facility area (sq. ft.)	10,000	10,000	12,500	15,000
Land and Building				
Total value ($000)	90	120	150	234
Annualized ($000)	17	20	25	34
Admin. costs ($000/yr.)	20.5	22	25	26
Annual Production ('000s)	15	20	40	32

a/ The number of employees (labor or staff) that report to the next higher level of management.

b/ This is the total for all types of machines. A detailed breakdown by type of machine is available upon request.

c/ This is the total for various equipment items. Different equipment types have different depreciation schedules, depending on their useful life. This, along with the long-term interest rate, determines the annualized rate for each item of equipment.

d/ The first number is the average number of hours between machine failures, and the second is the average time to repair the machine, also in hours.

e/ These are for inventory before and after the shop floor operations. Inventory on the shop floor (i.e., shop floor WIP) is calculated by the model.

Box 3.1 PRODUCT QUALITY A PROBLEM IN THIS MEXICAN COMPANY

Company X, a maker of stereos and radios for the domestic Mexican market, faces many factors contributing to its low product quality.

To keep costs low, company X produces many of the parts assembled into their products. For example, they hand coil wire to make transformers for power supplies and speaker voice coils, and manually operate simple stamping machines to stamp speaker cones. In both cases, these are processes that lead to low quality components in terms of poor reliability and function. Using many of these parts in their products leads to high system-level reliability problems. In addition, when Company X sets up the speaker cone stamping machine, they produce cones for a full day. This leads to a large inventory of cones that does not get depleted for a very long time. These cones are stored casually, often deteriorating in the environment, and causing already mediocre quality parts to only get worse.

Until Mexico joined General Agreement on Trade and Tariffs (GATT), Company X could only source parts from within the country, a practice they have continued to some degree. Domestic parts manufacturers often provide low quality parts at high prices and in inadequate volumes with erratic deliveries. Even so, Company X does not inspect incoming parts. Raw materials and components are simply used as received. However, incoming sub-assemblies are usually given functional tests.

Company X has almost no formal manufacturing planning and control mechanisms to schedule materials flows and production activities, or to do capacity planning. Their large raw material and finished goods inventories are symptoms of this. Large production lot sizes are pushed through the production system, leading to large work-in-process inventories, which are stacked all over the factory floor. Also, often large lots of flawed products are made before the problem is noticed. The low process quality at the Company manifests itself in high repair rates. Often, printed circuit boards are sent back several assembly steps to be reworked. Company X tries to scrap very few units due to the cost of parts. While 100% of the products receive a final functional test, only simple inspections are conducted along the manufacturing process. The firm has a high rate of defective product returns from retailers.

The Director of the Company is aware of more advanced technologies for electronics assembly and mechanical production but feels unable to justify their cost. He also stated that sophisticated manufacturing planning and control or cost accounting systems have little value if the company is not selling products--a problem they face due to new competition from foreign manufacturers.

Finally, LDCs, like DCs, have a smaller span of control (the number of employees that report to the next higher level of management). A larger span of control leads to a "leaner" organization. It is characteristic that in an LDC or a DC, seven persons report to an immediate superior. However, in an NIE, a supervisor has 10 persons working under him.

3.4 Input Costs

ManuCost permits a detailed specification of the manufacturing process. The underlying model keeps track of production flows accumulating both time and costs. This time and cost accounting ability permits the valuation of scrap and WIP under different organizational and technological arrangements. Highlighting the importance of and measuring these cost elements (scrap and WIP) under alternative scenarios is, we believe, a major contribution of this study. Typically, choice of technique is studied in relation to capital and labor costs assuming efficiency of workflow. This study highlights how inefficient workflows can add to unit costs in a significant manner.

The costs of labor, capital, and land and facilities are specified in Table 3.2. The stylizations accord with generally perceived opportunity costs of these inputs. Interest rates are highest in the LDC and lowest in the DC; the ordering of labor cost is reversed. The "long-term" interest rate is used to value fixed capital and the "short-term" interest rate is used to value inventory and work-in-progress (WIP). The virtue of our modeling procedure is that sensitivity of total costs estimates to variations in input prices can be easily assessed.

<u>Table 3.2</u>: ECONOMIC PARAMETERS FOR BENCHMARK MODELS

Parameter	LDC. Manual	NIE. Manual	NIE. Automated	DC. Automated
Production labor				
Wage ($/hr)	1.00	2.25	2.25	12.00
Benefit rate	33%	27%	27%	33%
Indirect labor a/				
Salaries ($000/yr.)	8-30	18-36	19-38	27-54
Benefit rate	33%	27%	27%	33%
Long-term interest rate %	12	10	10	8
Short-term interest rate %	25	20	20	15
Facility cost ($/sq.ft)	8	12	12	15.6

a/ The figures shown are the ranges of salary for different categories of employees. A detailed breakdown of employee categories and corresponding salaries is available on request.

Costs of equipment and land and buildings are the sum of depreciation (using the "straight-line" depreciation method) and interest costs with respect to the current valuation of the asset. Thus if equipment has a value of $V, a depreciation life of Y years, and the "long-term" interest rate is i%, the annualized cost will be V(1/Y + i/100). Different types of equipment are assumed to have different depreciation rates and these are not reported here.

Unlike other inputs, which have been specified in physical terms, material inputs have been specified in US$/PCB. This has been done mainly to avoid clutter, since the list of actual inputs is long. The benchmark assumes that prices of inputs are the same in all country types, and so the equality in the dollar value of inputs across country types also implies that the quantity of inputs is the same. This is not necessarily a realistic assumption. It is likely, for example, that certain inputs (such as PCBs and components) are more expensive in an LDC than in a DC from which they are transported. However, since our main focus is on the manufacturing process, we have chosen to control the material prices at the same level in all countries.

It should be noted though that certain indirect costs of importation (and delays involved in that process) are included in the higher levels of inventory in LDCs. Moreover, the input costs specified here should be interpreted as the minimum required for every finished PCB. In addition, as discussed below, some material is wasted during the production process. The lower the production "yields", the greater the wastage. We indicate a range of yields, the lowest prevailing in the LDC Manual factory. As a consequence, greater scrap raises the effective material input per unit of output.

3.5 Benchmark Costs

The manufacturing parameters (Table 3.1) and the economic parameters (Table 3.2) are the inputs to ManuCost. ManuCost estimates the work-in-progress and the value of the scrap, based on the operational characteristics specified, to arrive at final costs of production. ManuCost also tracks the time during which labor and capital equipment are actually being used. On that basis, it is possible to break down the use of labor and equipment into what we term "productive" and "unproductive" use.1/ When machines or workers are not being used, we term them "unproductive."

The NIE factory is the most cost competitive (Table 3.3). Higher unit costs in the DC are explained by higher labor costs (direct labor wages, management salaries and numbers of workers and managers). Even the higher value of scrap in the DC is a reflection of the value added (and hence essentially labor costs) in the material wasted and discarded.2/ The DC firm is

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1/ "Non-productive direct costs" are computed for both equipment and labor. Examples of non-productive times are equipment waiting for labor, equipment that has failed, and unused capacity of equipment or labor. Higher non-productive costs reflect an imbalance in the production line or production inefficiencies due to machine down time.

2/ During the entire accumulation process, whenever scrap is generated in manufacturing, the full value of the scrapped items is noted. The valuation of scrap includes the cost of raw materials as well as any direct and indirect costs accumulated in that item. For example, labor and capital costs incurred on the production of the item scrapped are included in scrap value. Moreover, if, at an intermediate step, additional raw material is required due to high scrap in the process, this additional cost will not show up in the "material" category but, rather, in the "valued scrap" category.

also somewhat less efficient than the NIE firm in terms of manufacturing parameters such as cycle times, yields and inventories.

That LDC costs are higher, compared with NIE costs, is more directly attributable to inefficiency. The basis for this inefficiency was described above when discussing the manufacturing parameters. Two significant cost disadvantages that result from these inefficiencies are in scrap costs and WIP costs.[3] These more than wipe out any advantage in labor cost.

Table 3.3: COSTS PREDICTED BY BENCHMARK MODELS

	Cost per PCB (in US$)				Percentage of cost			
Cost category	LDC Man	NIE Man	NIE Auto	DC Auto	LDC Man	NIE Man	NIE Auto	DC Auto
Material	50.00	50.00	50.00	50.00	49.7	55.3	62.06	43.20
Direct labor	3.51	6.42	2.62	15.83	3.5	7.1	3.3	13.7
Direct equipment	2.23	1.87	10.05	12.76	2.2	2.1	12.5	11.0
Non-prod. direct labor	1.86	3.19	0.86	5.66	1.8	3.5	1.1	4.9
Non-prod. direct equip.	1.96	1.31	4.04	6.92	1.9	1.5	5.0	6.0
Indirect labor	8.83	11.12	5.72	11.73	8.8	12.3	7.1	10.1
Land and buildings	0.88	0.88	0.60	1.00	0.9	1.0	0.7	0.9
Administrative	1.08	0.97	0.60	0.76	1.1	1.1	0.7	0.7
Inventory and WIP	6.20	1.95	1.46	2.04	6.2	2.2	1.8	1.8
Valued scrap	24.10	12.65	4.63	9.09	23.9	14.0	5.75	7.85
TOTAL	100.65	90.37	80.57	115.79	100%	100%	100%	100%

A feature of these cost estimates that should be noted is the high proportion of material costs. As we shall see in the following chapters, despite the importance of labor costs in DCs, technical change and especially new organizational practices, have been directed significantly towards lowering material costs. Hence, many of the new organizational practices have direct relevance for developing countries.

In an NIE, it makes economic sense to automate. Note, however, that what we have here is not a simple substitution of capital for labor. In fact, the additional cost of capital ($11 per PCB) is about the same as the savings in direct and indirect labor costs ($11.50 per PCB). The real savings come from the much lower value of scrap ($8/PCB). Notice that even though the value of machines installed goes up tremendously with automation, the number of machines falls. A single automated machine does more than one task. Automation, in this case, also permits working to tighter specifications with fewer errors.

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[3] The quantity of WIP predicted in the manufacturing model, and the short-term interest costs, leads to the WIP carrying costs. The calculation is more complex than a simple multiplication for two reasons: i) The WIP carrying cost at the first operation increases the valuation of the WIP for the second operation, and so on, and thus the WIP carrying cost needs to be computed progressively; and ii) The presence of rework leads to "feedback" where the outputs of a downstream operation affect the inputs of an upstream operation. This requires a system of equations to be solved to get the WIP valuation.

4. VARIATIONS AROUND THE BENCHMARK

Before considering the more fundamental changes to the PCB assembly process in the next two chapters, we examine how anticipated changes in wage rates, automation by LDC firms, reduced complexity of product and process, and increased scale of production affect the competitive ability of the three country types.

4.1 Wage Rate Changes: Through-Hole Technology

Current trends strongly indicate that wage rates will increase more rapidly in NIEs than in LDCs. The question we need to ask, therefore, is: Will a dramatic increase in wages in NIEs be sufficient to render them uncompetitive?

Starting from the benchmark model, we increased first the wage rate of only direct workers by 50 percent (from $2.25/hour to $3.38/hour). The estimated cost is presented in Table 4.1. The unit cost of an NIE firm, using manual technology, goes up from $90.40 to $95.90, an increase of $5.50. Even after this increase, LDC costs are still higher by almost $5 a board and DC costs are substantially higher. If NIE indirect worker wages also increase by 50 percent, total costs go up by a further $6 per board, eliminating any NIE cost advantage over LDC production.

Table 4.1: EFFECTS OF WAGE RATE CHANGES

Country Type	Technology	Benchmark Unit Cost ($)	Change Implemented	New Unit Cost ($)
NIE	Manual Through-Hole	90.37	50% increase in direct labor wage rate (from $2.25 to $3.38/hr)	95.85
DC	Auto Through-Hole	115.79	20% decrease in direct labor wage rate (from $12.00 to $9.60/hr)	111.18

It is, therefore, easy to understand the pressures for automation in NIEs. A 50 percent increase in wages and salaries (of direct and indirect workers) leads to a much smaller cost increase ($5 per board) when the process is automated, maintaining a strong NIE cost advantage over LDC or DC competitors.

Similarly, it is common for DC firms to complain that their lack of competitiveness arises from their very high wages. What would happen if DC wages fell? A 20 percent decline in DC worker wages (from $12.00 to $9.60/hour) results in only a $3.60 unit cost decrease, a fall of less than 3 percent. Again, a wage decrease of this order leaves unaltered the relative rankings of the different country types.

The main moral of these exercises is that even the basic automation described up to this point has resulted in wages becoming a small fraction of total cost and, therefore, large changes in wage rates cannot dramatically change relative competitive levels. NIE firms have largely anticipated wage increases and levels of automation described up to this point are widespread.

4.2 LDC Automation

Many LDC firms have automated through-hole assembly, to varying degrees. Automatic insertion machines are not uncommon. Less common is automated wave soldering. Modern automated testing procedures are least common.

By adding $684,000 worth of equipment (for insertion, soldering and testing), we make the LDC assembly line identical to the NIE assembly line in physical appearance. However, we continue to assume that the operational characteristics of the LDC line are inferior to those of a DC line which, in turn, is assumed to be inefficient compared to an NIE assembly line Relative to a DC-Auto case, set up and run times are longer (by about 6 percent), raw material and finished goods inventories are larger (approximately double), and repair and scrap rates are higher (25 percent).

Automation brings down unit costs even at LDC wages, but only by 3 percent (See Table 4.2). As in the NIE automation case described in Chapter 3, capital equipment is substituted for labor. In addition, the amount of scrapped material declines. Automation does less well in an LDC than in an NIE for two reasons:

- LDC wages are lower and therefore displacing labor has less economic value.

- Equipment usage in an LDC is poorer, making the cost of capital higher than in an NIE.

Nonetheless, automation brings other benefits. Manufacturing lead times decrease as automation dramatically lowers insertion times. For example, the insertion time for a set of transistor-type parts falls from 14 minutes to one minute.

The overall superiority of automation, even at low wages, in this assembly process is similar to the superiority achieved by automation in other industries we have studied (including certain types of garments, automobiles, and steel). The trend is clear. Automation is becoming cheaper and the advantage of automation will continually be reinforced. However, our analysis also shows that certain steps must be taken before introducing automation, particularly when automation is introduced selectively. Methods to improve equipment usage are critical. Such methods are, moreover, integral to reducing work-in-progress. They are discussed in detail in the next chapter.

Table 4.2: AUTOMATION OF PCB ASSEMBLY IN AN LDC

	Benchmark Process		Simplified Product and Process	
Cost Category	LDC Manual	LDC Automated	LDC Manual	NIE Manual
Material	50.00	50.00	25.00	25.00
Direct Labor	3.51	1.42	1.78	3.38
Direct Equipment	2.23	12.56	1.51	1.28
Non-productive direct labor	1.86	0.65	0.84	1.00
Non-productive direct equipment	1.96	7.39	1.15	0.66
Indirect labor	8.83	5.86	6.82	8.09
Land and Buildings	0.88	1.05	0.59	0.50
Administration	1.08	1.18	0.65	0.50
Inventory and WIP	6.20	6.09	2.78	0.84
Valued Scrap	24.10	11.69	5.96	3.35
TOTAL	100.65	97.89	47.07	45.29

4.3 Reduced Complexity

Since the two important factors raising LDC costs above NIE costs are the higher values of inventories and scrap in the LDC, the question we have asked ourselves is: Is this disadvantage critical in a case where the product and process are much simpler than they are in the benchmark case?

The answer is provided in Table 4.2. A new scenario was developed to represent a very simple manufacturing process corresponding to a very simple product. While the benchmark had six insertion stages and three test/repair/scrap stages, the simplified process has only three insertion stages and only one final test/repair/scrap stages. The simpler process also requires half the parts and half the input of utilities and facilities. The cost of the simplified board is, therefore, much lower than the benchmark board. Moreover, for the simpler process/products, the gap between LDC costs and NIE costs is almost eliminated. Relative to the more complex benchmark process, LDC scrap levels are much lower in the simplified process (falling from 24 percent to 12 percent of total costs) since process simplification reduces the possibilities of making errors. However, process simplification does little to reduce input and output inventories or even work-in-progress, which depends on parameters such as machine cycle times and reliability that do not change when the process is simplified; as a consequence, the share of inventory and work-in-progress costs remains at 6 percent of total costs.

The important lesson, however, is that even for a board that is directed to what may be considered a bottom of the range end product, the potency of scrap and inventory costs remains great. Though the gap in costs between LDC and NIE production is now small, it is still not the case that an inefficient LDC producer can increase market share solely on the basis of low wages.

4.4 Economies of Scale

A question of interest for developing countries is whether automation has any impact on the minimum efficient scale of production. Economies of scale are said to exist if output can expand faster than inputs (such as facilities, administrative overhead, and capital equipment), resulting in a lower unit cost at higher levels of output. It is sometimes suggested that modern automation technologies are modular in nature, and hence production overheads can be scaled very closely to output. In that case, unit costs will change very little with output change.

We do find that, for the degree of automation assumed in our benchmark models, scale has a minimal effect on unit costs. In an NIE through-hole automated factory, a doubling of output results in a 2.5 percent decline in unit cost. This result is the consequence of:

- the modularity of the technology.
- the low contribution of capital costs to total costs (only 14 percent in the benchmark model). The process is not very capital-intensive to begin with, hence there is not much capital over which to spread the output.
- our starting assumption that the factory is optimized in performance, and hence operates with very little slack. Often perceived economies of scale reflect only better capacity utilization.

Unfortunately, this finding does not strike a decisive blow for the argument that economies of scale are weak or even non-existent. Further levels of automation are being introduced. Our NIE and DC SMT factories, described below, experience a 5% decline in unit cost on doubling of output, a small but not negligible advantage in a highly competitive market.

Moreover, our analysis allows us to determine only the extent of scale economies that can be attributed to the technology of production. Much of the reshuffling occurring in the electronics industry is due to what can be called "organizational scale economies." The ability to source inputs in larger quantities, to distribute the output through a given set of marketing channels, and to allocate capital through internal allocation procedures can create scale efficiencies for the entire organization.

Indicative of increasing scale economies is the growth of contract manufacturers specializing in the assembly of PCBs for large numbers of customers producing many different end-products (See Box 4.1.). Though contract manufacturing remains a small portion of all PCB assembly, it is rapidly increasing market share. Contract manufacturers tend to use the most sophisticated production techniques which allow them the high degree of production flexibility essential to their business. Leading contract manufacturers are integrating forward into their own end-products and are setting up new facilities worldwide to be close to their customers.

4.5 Conclusions

The importance of materials costs in total production cost, and hence the critical role of materials management (to reduce scrap and inventories) have been highlighted by the scenarios presented in this chapter. LDCs can derive limited solace from the expectation that NIE wages will rise rapidly in the coming years. NIEs have largely anticipated wage increases through adoption of the technically and economically more efficient automated processes. This ability to anticipate technical change and rapidly come down new learning curves is the most important source of NIE competitive advantage. Neither can DCs hope to compete by merely striking better wage bargains with workers. Automation lowers costs even in an LDC. Costs are lowered not because automation saves on labor, but because it reduces scrap rates, thus saving on materials. There is little question that automated component insertion and soldering will need to spread rapidly in LDCs if they are to maintain competitive ability in international markets. However, that is likely to create further demands on organizational learning, whose importance and constraints are discussed in the next chapter.

Production of boards with low complexity significantly reduces the cost gap between LDC and NIE production. But even at low complexity, higher LDC inventory costs can prevent LDC firms from gaining large market share.

Economies of scale provide limited cost advantage in the current generation of technologies, though the advantage may be increasing at the higher levels of automation being currently introduced. Organizational scale economies may be increasing in importance, as indicated by the spread of contract manufacturing.

Box 4.1: CONTRACT MANUFACTURING BOOM IN DCS

Developed country manufacturers of electronic end products--the so-called original equipment manufacturers (OEMs)--are relying increasingly on contract assemblers, and making greater demands on them in areas from product quality to product design. In some cases, OEMs are asking sub-contractors to design and develop new products based on a general idea, rather than handing them detailed engineering specifications. Perfect shipments are expected; any defect is the sub-contractor's responsibility.

According to Technology Forecasters, a Berkeley, CA.-based market research group, total worldwide value of contract assembly will grow from $11.2 billion in 1989 to $18.7 billion in 1993, significantly faster than all PCB assembly. Some portions--notably SMT assembly, which currently represents about half the contract assembly market--will grow even faster.

Though growing very rapidly, contract manufacturing accounts for less than 5% of all PCB assembly. In an attempt to increase profits and satisfy customers, contract manufacturers are investing in the latest automation, concentrating on improving quality, and being flexible to comply with market demands. Some are moving to higher value-added products, such as more complex boards, and offering more design services aimed at shortening the design-to-fabrication cycle for their customers' benefit. In fact, the subcontractors are becoming so capable that some are beginning to consider developing their own end-user products.

The bigger contract manufacturers, such as SCI Systems, Solectron and Flextronics, are also expanding into Europe and the Far East to serve their local customers globally. In fact, most of the recent employment growth of these three leading U.S.-based contract manufacturers took place in Europe and the Far East, because their clients demanded it.

As in Japan, U.S. OEMs are recognizing that they need a symbiotic relationship with subcontractors. For example, when Dynacircuits Inc., a small U.S. manufacturer of single-sided PCBs, developed a training program, instituted a statistical-process-control program and designed a quality-operating system, it had the help of a large customer: Ford Motor Co.

Source: Electronics Business, September 17, 1990.

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5. LEARNING TO PRODUCE

5.1 Objective

The state of manufacturing practice in a firm or a country is the result of organizational and shop-floor learning that has been undertaken in the past. The learning experiences of others may sometimes be embodied in advanced machines, reducing the further need for "soft" investments in worker training, improved work practices, and organizational changes. However, a central proposition of this study is that these so-called soft investments, for which we use the short-hand term "learning", are critical to international competitiveness.

We view learning as a process of experimentation aimed at increasing productivity. As such, it is something of an art form. However, modern tools and practices embodied in, for example, Total Quality Control (TQC) and Just-in-Time (JIT) provide structure and content to the learning process by specifying the elements of training, organizational change and infrastructure needed to continuously improve the production process.

In this chapter, we evaluate the quantitative impact of improved production practices that overcome inefficiencies in the production system. The procedure we follow, as in the previous chapter, is to generate a set of "scenarios." These are "what-if" exercises and, as such, are purely accounting devices that say nothing about how the transition is made from one state to another. Hence, after demonstrating the quantitative impact of a change in factory operating procedures and practices, we discuss issues relating to their implementation.

The first set of scenarios brings the LDC and DC factories on par with the NIE factories in terms of manufacturing parameters. The manufacturing parameters of the NIE factory can be considered the "current best practice," so this first set of scenarios brings everyone to the current best practice. The cost differences that remain at the end of this sequence are due to differences in costs of inputs.

However, the current best practice in the NIEs is a moving target. Trends indicated in the literature and our field interviews suggest clearly that further improvements in production management will occur in the next five years. These are modeled as future best practice.

When we "move" a factory from its benchmark level of efficiency to current best practice and then to future best practice, we are assuming that the relevant learning process is in place. Learning, however, is not a trivial task, it is costly both for the firm (e.g. investment in training) and for the economy (e.g. provision of relevant infrastructure). These costs are not easy to quantify, and so are discussed qualitatively. We conclude that either these costs are so high that LDC firms should not be producing even a product as technically mature as the one considered in this study. Or, on a more positive note, we could conclude that significant efforts to generate such learning are needed urgently if LDC firms are to be competitive in international markets.

5.2 Current Best Practice

The following changes were implemented sequentially:

Improved process efficiency: Scrap rates, machine reliability and in-house buffers were all brought to NIE levels. We start with these changes because these are internal to the firm and thus presumably under greatest control by the firm.

Reduced inventories: Raw materials and finished goods inventories were brought to NIE levels. These changes typically require cooperation from suppliers and buyers and from the transportation and communication system. However, large inventories cannot be blamed entirely on others' shortcomings. Better production management, greater specialization in procurement and composition of production can all help to reduce inventories.

Reduction in cycle times: Process cycle times were brought to NIE levels. Once inventories are reduced, there is pressure to shorten production lead times. This brings additional benefits, principally lower work-in-progress, higher capacity utilization, and the ability to produce greater product variety. Reduction in cycle times requires better quality machines, superior maintenance, and also internal capabilities in organizing the flow of work.

Improved management and overall operation: Span of control, absenteeism, facility area, and days worked per year were all brought to NIE levels. For the DC, days worked per year was left at 240, as working on Saturdays was felt to be unrealistic.

The effects of all these scenarios on the cost of an assembled PCB are summarized in Table 5.1.

Table 5.1: STEPS TO CURRENT BEST PRACTICE

	Cost per PCB (in US$)			
	LDC Manual	NIE Manual	NIE Automated	DC Automated
Benchmarks (as before)	100.65	90.37	80.57	115.78
Steps to current best practice:				
Internal process improvement	87.16	-	-	110.30
Reduced inventories	83.85	-	-	109.72
Reduced cycle times	83.47	-	-	106.59
Improved management	81.23	-	-	104.53

Recalling that the practices are introduced cumulatively, an LDC producer of PCBs saves $19 per unit (an 18 percent decline in cost) by improving production and management practices. Over $13 of the gain comes from internal process improvements such as reduced scrap rates, higher machine reliability, and lower in-house buffers. A further $2 is gained through improved management (larger span of control, reduced absenteeism). Thus almost 80 percent of the gains come from internal improvements, implying that the major weakness lies within the firm. Inventory reduction, which depends more (though not entirely) on factors outside the direct control of a firm, lowers unit costs by $4 (about 20 percent of the cost reduction).

The significant payoffs from these improved work practices indicate an important role for enabling infrastructure. High machine reliability requires strong maintenance engineers and technicians both within the firm and outside. Reduced scrap rates require that the materials supplied be of high quality. Standards institutions to diffuse quality control, measurement and testing techniques, and machine calibration have a very useful role to play. Good communications and transportation are obvious needs.

Once all the production and management inadequacies have been removed, an LDC, not surprisingly, becomes almost competitive with an NIE. Even when using manual technology, an LDC firm produces at about the same cost as an NIE firm using automated methods. As discussed in the next chapter, an LDC can gain further from automation.

A DC firm also gains significantly from the same process improvements. The source of the gain is, however, somewhat different from that in an LDC. We have made the assumption that the DC firm is more efficient than an LDC firm (though less efficient compared to an NIE firm). However, a DC firm uses more expensive equipment and labor. Hence inefficiency is more expensive in a DC. It will be recalled that our value of scrap measure estimates not just the value of material scrapped but also the value that has been added to the scrapped material. When machinery and workers are expensive, a small amount of scrapped material can lead to great overall wastage.

5.3 Future Best Practice

Countries that have invested in the learning process (the NIEs) have developed a cost advantage that they are able to sustain by continuously redefining the frontiers of the "mature" technology. We expect such redefinition of the frontier to continue. Looking five years into the future, we develop a second set of scenarios. These scenarios take the manufacturing parameters of all the factories from the current best practice defined above, to a possible "future best practice." The following changes are implemented simultaneously:

- A further reduction in scrap and repair rates (by 50 percent).
- Doubling of mean time between machine failure (any equipment used, such as a solder iron or functional tester, lasts twice as long before it fails).
- Raw material and finished goods inventories reduced by half.
- Process cycle times reduced by another 10 percent; set-up times reduced by 25 percent.

- Span of control raised to 20 and facility area reduced by a further 15 percent.

These represent the outcome of learning-by-doing on the shop floor. Change is incremental and the result of extensive planned experimentation by workers, managers, technicians and engineers. Firms achieve such learning through a variety of self-reinforcing means, which we discuss below.

When these changes are implemented, an NIE employing automated assembly would lower costs by $6 per PCB (an 8 percent decline) to $74 (Table 5.2). An LDC that remains at the benchmark will produce a stuffed PCB at a cost that is $26 higher than the ever-leaner NIE firm. A cost difference of that magnitude would mean that the LDC would find it almost impossible to enter international markets. When we allow also for the near-certainty that the NIE would be delivering a more consistent product on time, the competitive position of a lagging LDC becomes completely unsustainable.

Table 5.2: FUTURE BEST PRACTICE*

	Cost per PCB (in US$)			
	LDC Manual	NIE Manual	NIE Automated	DC Automated
Benchmark	100.65	90.37	80.57	115.79
Current Best Practice	81.23	90.37	80.57	104.73
Future Best Practice*	74.23	77.53	74.43	97.56

* Authors' predictions of unit cost in five years based on assumptions regard process learning discussed in the text.

An LDC firm that moves to "future best practice" begins to approach international competitiveness. The interesting point to note is that, even after we make the assumption that the LDC firm keeps pace with an NIE firm in improving its production process, LDC costs are only marginally lower than those of an NIE. The slightly lower wage costs of an LDC are balanced by its higher interest costs. If LDC firms undertake massive shop-floor improvements and NIE wage rates rise rapidly, then the LDC advantage would be more substantial.

The move to "future best practice" also reduces the DC-NIE cost gap. The streamlining allows the DC firm to reduce not only its inventories and scrap, but also its labor cost. However, the cost difference continues to be substantial, implying that DC firms need to differentiate their products considerably in order to be successful. This explains why Japan, though proficient in production technology, took the lead some years ago in moving away from through-hole to SMT process technology, which permits much greater product flexibility and differentiation. U.S. and other Western producers are following Japan's lead.

Just as NIE firms moved to automated processes in anticipation of increased wages, we see here a more striking example of developed country firms anticipating loss of competitiveness and therefore moving to a very different process technology. NIE firms are not standing still in the meantime: they are experimenting with SMT processes and should soon acquire significant proficiency. However, developed country firms are preparing for that onslaught by investments in even more ingenious technologies (See Appendix A).

5.4 The Learning Process

Japanese and other East Asian firms have made an art form of continuous incremental change that, over time, leads to major gains in productivity. The art is being gradually codified into techniques covered under the rubric of just-in-time (JIT), of which total quality control (TQC) is a subset.

These modern techniques of organizational change offer significant possibilities for manufacturers in LDCs. Our cost analysis has shown that adoption of these techniques restores the cost advantage of LDCs over NIEs. Scrap and inventory reduction under JIT are especially beneficial to LDCs. Reduction in waste confers an obvious benefit and high interest rates make it punitive to maintain large inventories.

The deceptive charm of JIT also is that there appear to be no costs associated with implementation. However, implementation of any change is an expensive activity and JIT is no exception. More importantly, JIT implementation is expensive in a resource that LDCs are not well-endowed with: human capital. Implementation requires tuning the technology to the organization and tuning the organization to the technology (Leonard-Barton 1988 and Schroeder, Gopinath and Congden 1989). The skills required for such tuning include both formal training (to understand the principles underlying the technology and the theory of organizations) and experience in implementing change.

In addition, there are costs due to lost production during the period of implementation and more conventional costs of buying new equipment and hiring consultants.

It is also good to keep in mind that implementation of new technologies and practices in LDCs occurs in a context that is not conducive to change. The ability to source inputs in a timely manner from specialized producers is critical to the full implementation of JIT. This requires good physical communication, but it also requires the growth of specialized suppliers working in a cooperative mode with their buyers. Infrastructural deficiencies, regulatory barriers, and constraints on input supplies are some of the handicaps from which firms in developing countries suffer. Firefighting on these fronts is very expensive in terms of scarce managerial and entrepreneurial resources.

We discuss below these specific costs of JIT implementation in some detail.

Training and Organizational Change

While popularly viewed as an inventory reduction practice, JIT is an organized process of incremental change aimed at creating a closely integrated flow of work. JIT requires microscopic attention to detail and is aimed at streamlining procedures, reducting set-up times and scrap rates, improving machine reliability, reducing variability of production flow, and such like. Such internal efficiency measures make lower inventories possible; in turn, lower inventories unmask further inefficiencies and force changes. Greater decentralization of decision making (reduced span of control) reinforces these efforts by generating more information from the shop-floor, feeding the process of continuous minor modifications.

The process of implementing JIT is experimental in nature; however, well-defined techniques exist for such experimentation. The JIT toolbox consists of: industrial engineering techniques to reduce machine set-up times and facilitate easy changeovers in the use of machines; methods for streamlining plant layouts; techniques for quality control and maintenance; and organizational and engineering techniques for simpler product design (Zipkin 1991). Thus the most important investment required for implementing JIT is human capital. Only a workforce that is well-educated and trained can use these tools effectively.

Training takes many different forms. Workers may be sent to external institutions, such as local community colleges and vocational schools. Within the firm, formal courses may be organized or training may be imparted in many informal ways.

Japanese scholars have emphasized that the so-called informal training is probably the most important and most effective form of training for improved shop-floor productivity (Koike 1988). The important observation is that improvements are brought about by line workers who do not necessarily possess industrial engineering diplomas and degrees. However, effective supervisory support is crucial.

Informality in this context does not imply a lack of training plan or direction. Paradoxical as it may sound, informal training requires a strong institutional commitment and well-defined process. Limited reliance on the classroom is the main reason for using the term "informal". Mentoring by supervisors, collaborative problem solving with peers (quality-circles), job rotation through the plant and the firm are the more important elements of informal training.

The message on training is clearly out. U.S. firms attempting the adoption of JIT techniques are making serious efforts to institutionalize formal and informal training processes within firms. (See Box 5.1)

A closely related concern that interacts with training is the need for organizational change. Delayering the traditional organizational pyramid by expanding the span of control yields significant cost savings in companies located in all country types, but especially in those countries (DCs and NIEs) where the cost of management is high. Take the example of a factory employing 385 line workers. Using a span of control of ten; the plant requires 35 first level, four second level, and zero third level managers. Table 5.3 shows that a relatively small change in the span of control produces a dramatic change in the number of managers required.

Table 5.3: SPAN OF CONTROL EFFECTS

Managerial Level	Span of Control				
	3	5	10	15	20
Third-Level	13	3	0	0	0
Second-Level	39	14	4	2	1
First-Level	116	70	35	24	18

The greater gains from reduced span of control arises in the form of better information generation and decision-making. Workers close to the shop-floor have superior information on the work process and are potentially better positioned to rapidly analyze the information and take corrective measures before problems cumulate (see especially Aoki 1990 on such benefits in the Japanese context). These gains, however, are hard to quantify.

The pressure to increase span of control grows when greater emphasis is required on reducing lead times, improving quality, and increasing product variety. No longer is time available for problem-solving decisions to filter through several layers of management and companies must flatten their traditional hierarchy. They must train production workers in problem-solving techniques and, at the same time, empower them to implement solutions. Autonomy and decision-making authority must be transferred from management to the shop floor (Deming, 1986).

However, the ability to delegate depends heavily on the quality of both management and labor. Management needs to be trained in the tools of JIT and thereby simplify the tasks to be performed. On the other hand, workers need skills to take on the responsibility of interpreting the operation of the factory and discovering creative solutions to problems.

Given the limitations of both managers and workers, increasing the span of control may not be cost effective. Savings are possible only when greater responsibility can be safely delegated to the production line employee. This creates particularly severe pressures on LDC firms to invest in training. However, the ability to train is constrained by low basic educational attainments of the employees. Limited knowledge exists on the form and magnitude of training incentives to which LDC firms respond, and this is clearly an important area for further investigation.

Productivity "Dip" and Other Costs

In addition to the costs of training often overlooked is the cost of disruption in the manufacturing process that JIT causes by reducing inventories. Drastic inventory reduction, resulting in a shortfall of raw materials, will create idle stations and disrupt production - potentially to such a point that the problems incurred will cost the company more than the benefits to be derived from JIT. Known as the "productivity dip," this disruption is common and should be addressed prior to JIT implementation (Suri and DeTreville, 1986).

The financial costs of such disruption may be minimized by proceeding sequentially. Experience has shown that JIT should be implemented in stages, in carefully selected areas, rather than being adopted immediately, company-wide (Barrett, 1988). A step in the successful implementation of JIT is a carefully chosen pilot project. A pilot project helps gain the confidence of both managers and workers, and provides training to engineers and employees (Love, 1988). Starting with internal efficiency measures, over which the firm has more control, is a logical approach to implementing JIT.

Consultancy costs of developing and implementing JIT can be significant. In addition, LDCs tend to have underdeveloped consultancy services, particularly those directed towards small and medium-sized firms. Programs that tap and train private individuals (retired executives, university professors and graduate students, vocational school trainers, and capital goods suppliers) to work with small and medium-sized firms could have big pay-offs.

A network of government and industry run technology diffusion centers acts as a substitute (OTA 1990 and Cole 1989). National Bureaus of Standards and public and private productivity organizations, often organized by industry groups, play a very important role in technology diffusion. In Japan, for example, external consultants are used to a much smaller extent than in the United States. Diffusion centers are both a source of expertise and also a forum for exchange of lessons learnt.

Though JIT techniques are directed primarily at changing the organization, new machinery is often required (Zipkin 1991). Improving the quality of machinery is sometimes a prerequisite to achieving lower set-up times and greater machine reliability. Often production capacity also needs to be increased as inventories are being lowered in order to accommodate sudden surges in demand.

Infrastructure

Besides the obvious need for transport and communications infrastructure, unreliable suppliers also impede the movement toward JIT in LDCs. Manufacturers we interviewed most often cited the lack of reliable suppliers as an impediment to JIT in an LDC company. This perception needs to be interpreted cautiously. We have discussed above the importance of many internal improvements which lead to substantial productivity gains.

Manufacturers that have recently implemented JIT programs have reduced the total number of their suppliers, established long-term relationships with the remaining suppliers, and created certification programs for key suppliers.

Such programs are not without precedent even in LDCs. Recently, Caterpillar Inc., in conjunction with P.T. Natra Raya of Indonesia, has begun

Box 5.1: TRAINING AND EDUCATION FOR QUALITY

To achieve Total Quality Control (TQC), employees must be trained and educated in quality. Many electronics companies have intensive programs in this area. Three leaders in the field:

- Intel Corp., the United States' third-largest semiconductor manufacturer, greatly expanded its commitment to employee education after executives visited Japan in the early 1980s. Now training for workers extends over weeks or months, instead of days, and senior managers are included. Intel University, at five company sites in the U.S., offers regular classes to everybody, from shop floor workers to corporate management. They teach not only technical competence but also the Intel culture and general business skills. The approach is hands-on and practical; most courses are taught by experienced Intel employees, and learning is immediately reinforced with on-job application.

- Rockwell International Corp.'s Digital Communications Division is the leading supplier of facsimile modems in the world and sells most of its products to Japan. It achieved that position, management says, through a quality program that includes a five-year training schedule for all personnel associated with production operations, finance, personnel and marketing. Bottom-up training has focused on statistical process control methods for the engineering and production staff, and design of experiments training. On the factory floor, all operators must go through a skills-certification process every six months that insures they understand their jobs and have the appropriate skills. Lead operators also attend train-the-trainer workshops so they can teach other employees on the shop floor.

- Hewlett-Packard Co.'s corporate quality training curriculum, adopted in 1985, was borrowed heavily from its operations in Japan, Singapore and Malaysia. In fact, the name for the methodology, taught to managers, for planning and setting priorities is hoshin kanri, Japanese for "compass"; it teaches managers how to focus their attention on two or three critical issues facing the company or department, in addition to carrying on day-to-day business. For all employees, quality-improvement training - which averages 50 hours per worker - takes place on three levels: general TQC education, job-specific quality training and continuing education. Many aspects of the training, such as concurrent engineering practices, came from automotive and other industries.

Source: Electronics Business, October 15, 1990.

to qualify suppliers for its Indonesian factories. There are few such qualified suppliers in Indonesia now, but Caterpillar has offered training and technology to those suppliers willing to work toward qualification. Caterpillar thus hopes to manufacture in Indonesia internationally competitive products and components (Cat World, 1989).

Programs that supplement the initiatives of major international companies such as Caterpillar are needed to diffuse widely international standards in quality control practice and provide certification services.

Such programs are, in principle, no different from the general technology diffusion programs described above.

5.5 Summary

JIT may be considered the institutionalization of a learning process within the firm. Economists are used to thinking of "learning" in a somewhat mechanistic manner. Learning is often viewed as a costless by-product of production or investment. If that were the case, Eastern European firms would be amongst the lowest cost producers in the world. The reality is that learning is an expensive process requiring considerable experimentation with the production process and, more fundamentally, with the organizational structure of the firm.

JIT implies one or both of the following propositions: 1) human capital requirements, in particular, but also the need for physical capital, are so strong even for so-called "low end" products that most developing countries do not have a real comparative advantage in simple manufactured goods; 2) to overcome this disadvantage, access to international sources of knowledge and increased domestic investment in knowledge creation, with a clear focus on improving basic manufacturing productivity, must be a major priority for LDCs.

The implication is that greater experience with modern industrial practices is needed in a setting where such experience can be absorbed. Close links with foreign firms that possess the knowledge needed for efficient absorption is likely to be a must.

In the early 1980s, JIT was labeled a strategy possible only in the restrictive operating conditions prevalent in Japan. Today, U.S. manufacturers provide the success stories so abundant in the literature. They are learning to better manage suppliers, and the message on training appears to have sunk in. (An excellent example of integrated change is described in Box 5.2.) Not long ago the U.S. manufacturing environment was classified as not conducive to the use of JIT. Today the same is being said of the LDCs.

Box 5.2: Integrated Changes for Competitiveness

Three years ago, Company Y, a domestic manufacturing plant for a U.S. based telecommunications company, started responding to increased competition by drastically improving product functionality and reliability while reducing unit cost and manufacturing lead times.

Significant training programs for everyone from the general manager to shop floor workers were initiated. The firm has a large training center which educated plant workers on corporate identity and competitive objectives, manufacturing workmanship standards, and skills for JIT-style manufacturing. Mini-courses on quality management were given, and all machine operators were trained in statistical process control methods and now regularly plot control charts. Workers also took courses on specific technologies such as SMT.

Workers have incentives to increase their education and subsequently their skill grades to gain higher wages. Company Y aims to have employees "cross-trained," that is, capable of diverse tasks.

To support the change, Company Y increased their materials planning staff levels, but did away with the Quality Review department. This department traditionally conducted product inspections after major stages in the manufacturing process. The department's resources were reallocated to have continuous review of product quality throughout the process, not just at major stages.

Today, a shop floor worker can shut down an entire production line if she/he detects a quality problem, even if that problem is at another workstation. Additionally, workers can turn on a blue light signifying that they need more time to complete the task than is normally allocated by the computer controlled assembly line.

In addition, Company Y worked closely with its vendors to ensure timely delivery of parts, reduce shipment lead times, and most importantly, drastically increase incoming part quality. In some cases, quality was improved to levels that obviated the need for incoming parts inspection. The firm is still working to reduce the number of its vendors, and has a sole-sourcing objective.

As a result of the new technologies and managerial practices, Company Y cut manufacturing lead times from 40 weeks to 2.5 weeks, reduced operating space requirements from 16,000 square feet to 4,000 square feet, and drastically reduced all inventory levels.

The plant still faces computer integration problems with its automated guided vehicles (AGVs). Company Y is actively involved with the AGV vendor to modify the equipment's software so as to support integrated operation with other automated equipment. Company Y stated that "automation forces better flows." In preparation for increased levels of automation, the firm had to simplify the manufacturing process in terms of materials flows, number of workstations, proximity of equipment and diversity of part and operation types.

6. EMERGING TECHNOLOGIES

6.1 Two Major Developments

The two most fundamental changes occurring in PCB assembly are, first, the emergence of surface mount technology (SMT) as an increasingly dominant processing method and, second, the more incipient, though potentially more revolutionary, technique referred to as design-for-manufacturing (DFM) that drastically lowers production costs and at the same time enormously increases flexibility in introducing new product designs.

Both these changes should be viewed as the DC response to low wage competition. Unable to compete directly with lower wage producers, DC firms have shifted the emphasis of the competition away from merely low costs to superior product functionality and more rapid product obsolescence.

Surface Mount Technology. As electronic end products have become more sophisticated (in their range of functions and speed), through-hole boards have become too large and unwieldy. The drive towards miniaturization has led to the development of SMT. Printed Circuit Boards (PCBs) for surface mount assembly do not require holes since the components can be soldered directly on to the board with an electrically conducting material. The small size of SMT components and the precision required in placement has virtually dictated the use of automation in SMT assembly.

SMT's advantages are significant. The SMT components are much smaller than traditional through-hole components, allowing for smaller PCBs and, ultimately, smaller and lighter-weight products. SMT component assembly machines place many more parts per minute than through-hole machines. However, there are drawbacks. SMT is more sensitive to errors, requires more highly-skilled and educated workers, uses more expensive equipment, and, at this time, is subject to some problems in the availability of components and the absence of engineering standards.

Design-For-Manufacture. Traditionally, product design and development in the United States has been described as "sequential," because it involves only one corporate function at a time. Typically, it begins with the marketing group, which develops a "product concept" based on market research. Then the design engineering department designs a prototype, and manufacturing engineering configures the equipment to produce the product in volume. Once it is manufactured, the product becomes the responsibility of distribution, field service and other parts of the organization involved in sales.

Not only is the sequential process time-consuming, it can lead to the design and manufacture of sub-optimal products. Sequential approaches lead to functional areas performing their work in relative isolation, without consideration of downstream product requirements. Specifically, design engineering often neglects to examine how easy or difficult it will be to manufacture the product in volume, leaving that bridge to be crossed by the manufacturing engineers.

Integration and interaction between the different functional areas are the goal of the movement described as "design for manufacture".

6.2 Surface Mount Technology (SMT): Three Scenarios

We studied three scenarios relating to SMT. The benchmark SMT process describes current best practice. We present benchmark estimates only for DCs and NIEs since there is virtually no SMT in LDCs. Even the benchmark factory has a very high level of automation. A good example of a benchmark factory is provided in Box 6.1. As in the through-hole scenarios, operational efficiency in the DC is considered to be at a lower level than in the NIE.1/

We then consider the movement of the benchmark factory to future best practice (FBP) exactly as in the previous chapter. This move represents the learning that is expected to occur in process improvement over the next five years. It should be noted that, being a new process, SMT is likely to undergo considerable cost reduction through process improvements.

In addition, learning will occur in the factories of SMT component suppliers. This will again result in substantial cost declines.

6.3 Benchmark and Future Best Practice

SMT assembly is currently more expensive than conventional through-hole assembly. As a reference, the costs of through-hole automated assembly are presented in Table 6.1 along with the SMT assembly costs. Components are the principal contributor to the increase in unit cost; however, costs rise for almost every category listed.

The SMT process is more labor-intensive than the through-hole process in the DC, in the sense that the ratio of labor costs to capital is higher for the SMT process. This is despite the fact that SMT assembly is quite automated. The high labor input reflects the novelty of the technology and, hence, the ongoing learning process. Limited equipment range and weaker standardization have meant that SMT assembly lines are often more of a patchwork than are through-hole lines, requiring considerable human input. The quality of the (indirect) workers is also somewhat higher on an SMT line than on a through-hole line; hence, higher wage rates have been assumed for SMT assembly.

1/ The NIE SMT benchmark factory employs precisely the same manufacturing process (set of machines) as the DC SMT benchmark factory. Relevant operational parameters and input costs are as in Tables 3.1 and 3.2. For example, we make the assumption that NIE inventory levels are two-thirds of DC levels, given our perception of the superiority of inventory management in NIEs.

Box 6.1: STATE-OF-THE-ART SMT AT TEXAS INSTRUMENT

Surface mount technology (SMT) at its most automated can be seen at the Johnson City, Tennessee, printed circuit board factory of Texas Instruments Inc. The 4,300-square-foot facility, which gets 80 percent of its business from custom manufacturing for other companies, has attained a level of computer integrated manufacturing (CIM) that is virtually unmatched in the industry. Customers made it clear that they wanted SMT, and TI decided to adopt--or, in some cases, pioneer--the most advanced automation.

Thanks to the resulting CIM, the facility in its first two years produced 250,000 boards of more than 30 types--from PCBs for automotive window controllers to boards for high-resolution graphic workstations. Component densities range from 20 to more than 500 per board. For the shortest cycle time, the lowest inventory, plus the highest quality, "you just can't do without automation", says Richard A. Keenen, site operations manager at Johnson City.

Between 1987 and 1989, throughput increased to 250 boards per shift, from 200; first-pass electrical test rejects fell 28 percent; and raw material-to-ship cycle time was cut to three days, from five. However, CIM is a "moving target". James A. Almond, manufacturing services manager for the facility, says: "Three years ago we would have thought we had 100% CIM. Right now, we think we have 60% CIM".

The process combines flexible assembly cells with automated materials handling, tied together with three levels of computers. A total of 12 to 15 people run the manufacturing facility with an annual turnover in 1989 of about $40 million.

Unit-level computers are usually built into the machines; cell-level computers handle supervisory functions and respond to data from the unit-level computers; and area-level computers interface with plant and corporate information systems. Computer-aided-design (CAD) data for new boards and design changes is transmitted to the supervisory computers. The entire network can also be tied into customers' computers, to allow real-time interaction for process specification and design change. As a measure of the operation's exceptional quality control, there are no people doing touch-up work at the end of the solder line.

TI's immersion in CIM has not been painless. The complexity of the SMT machinery necessitated a year of training, compared to the three or four months required for through-hole machines. The complexity also lowered initial uptime to 60 percent, although it has since been raised to 90 percent. Because the factory builds three or four different board types a day, the company is working hard to reduce changeover time.

The Johnson City facility is a small volume operation. The success has induced TI to pursue contract manufacturing in other plants; moreover, some of the lessons are being transferred to TI's high volume operations.

Source: Electronics Business, March 6, 1989.

Table 6.1: SMT ASSEMBLY COSTS

(Cost per PCB in US$)

Cost Category	NIE Through-hole Automated	DC Through-hole Automated	NIE SMT. Benchmark	DC SMT Benchmark	NIE SMT FBP *	DC SMT FBP *
Material	50.00	50.00	65.70	65.70	65.70	65.70
Direct Labor	2.62	15.83	4.12	22.95	3.32	18.53
Direct Equipment	10.05	12.76	13.66	15.66	11.24	12.91
Non-prod. Direct Labor	0.86	5.66	1.86	9.59	1.38	7.70
Non-prod. Direct Equip.	4.04	6.92	8.27	8.75	10.84	7.54
Indirect Labor	5.72	11.73	10.75	17.95	9.26	12.97
Land Buildings	0.60	1.00	0.77	0.88	0.67	0.77
Administrative	0.60	0.76	1.05	1.14	1.05	1.17
Inventory and WIP	1.46	2.04	2.21	2.66	1.01	0.93
Valued Scrap	4.63	9.09	6.83	8.30	2.78	3.15
TOTAL	80.57	115.79	115.22	153.58	107.27	131.36

* Future Best Practice

Many workers on SMT lines are currently experimenting with the process and are trouble-shooting. Greater control over the process is being acquired through experimentation with different process parameters and a number of problems in such areas as soldering have been resolved. See Box 6.2.

Lack of equipment standardization and process standardization has slowed adoption of SMT in the past. However, rapid change is occurring. Equipment vendors have also made substantial efforts towards standardization.

For these reasons, we would anticipate that the cost differential between the SMT and through-hole technologies will rapidly decline. As in the previous chapter, we project best practice costs five years from now. As Table 6.1 shows, our projections for "future best practice" are a 7 percent cost decline for NIEs and a 12 percent cost decline for DCs. The larger cost decline for a DC reflects the assumption that current practice in an NIE is superior to that in a DC today.

6.4 Materials Price: SMT

Similarly, component suppliers are improving their capabilities and, as the market for SMT components expands, are achieving greater economies of scale. Given the rapid gains in learning about the production of SMT components, it is widely predicted that the price of inputs will fall significantly over the coming years. This will clearly make SMT more competitive with through-hole technology, since the cost of SMT components will drop much faster than through-hole component costs.

We examine here a scenario under which SMT component costs decline by 25 percent, a relatively conservative projection within the framework of the next five years. Material costs for the PCB substrate and parts, therefore, fall from $65.70 to $49.30. The cost of additional parts used at repair stations also falls by 25 percent.

Box 6.2: ADOPTION OF SMT REQUIRES SYSTEMATIC PLANNING

In the mid-1980s, electronics experts were forecasting that surface mount technology would be used for all PCB assembly by 1990. However, adoption of SMT has been slower than expected. In 1988, surface mounted packages accounted for only 17.5 percent of the world market. A report in 1989 predicted that SMT would have a slight majority--52 percent--of the total market by 1993.

SMT has made deeper inroads in some countries than in others. In Japan at the end of the last decade, SMT had a market share estimated at between 50 and 60 percent. It was reported to be 25 percent in Europe, where the companies adopting SMT include Italtel, Olivetti, Nixdorf and Siemens. In the U.S., where SMT was pioneered by the big automakers and has more recently been adopted by the computer industry, market share was said to be only 15 percent. Presumably it is in single-digit figures in the developing world, although SMT has been introduced in China.

A number of factors account for SMT's slow growth. European manufacturers found a shortage of surface mount components, necessitating a mixing of conventional assembly and surface mount equipment. Furthermore, surface mount components are also difficult to handle and more expensive, and mixed technology (combining through-hole with SMT) is expected to continue for some years.

In general, however, it is the newness, complexity and cost of SMT that have impeded its progress and given it a reputation for poor yields and tricky manual rework requirements. The board design raises problems due to increased density, closer pin spacing, higher temperatures and an ever-changing library of parts. But manufacturers who have implemented it successfully say that, with systematic planning and SMT-appropriate product design, costly equipment and process errors can be avoided.

One of those is Datamedia Corp., a Nashua, New Hampshire company that implemented SMT in 1987. Initially, the company had only a limited knowledge of SMT. What characterized Datamedia's approach--and ultimately turned its implementation of SMT into a success--was intensive front-end planning and constant communication among designers and component engineers, learning and manufacturing engineers.

The company created a "road map" of where it wanted to go: a high-quality board that mixed through-hole and SMT; a high level of automation; and flexibility to accommodate new designs and boards ranging from 4 x 5 inches to 16 x 20 inches. The process began with the fabrication of a fairly primitive prototype assembly line. During a three-month period, the company manually assembled and tested more than 100 boards, evaluating test and repair issues and formulating a general approach.

Engineers spent a great deal of time on "what-if" scenarios that might require changes in equipment layout. They obtained data on available equipment through technical publications and shows, as well as visits to factories where SMT processes were being used. It was only then that Datamedia chose capital equipment. From inception to full production, the entire process took ten months. The learning process continues.

Source: Manufacturing Systems, August, 1988.

The change in unit costs following a decline in materials input prices is substantial (in the range of 10 percent) (See Table 6.2). While this still leaves SMT more expensive than through-hole assembly, the gap is considerably narrowed. Also, because SMT boards typically have higher value than through-hole boards, a direct comparison of unit costs alone may be somewhat misleading.

Table 6.2: SMT INPUT PRICE DECLINE

Country Type	Technology	Benchmark Unit Cost ($)	Change Implemented	New Unit Cost ($)
NIE	SMT	115.22	25% decrease in input cost	97.00
DC	SMT	153.58	25% decrease in input costs	135.30

6.5 Diffusion of SMT

Typically, manufacturers that use SMT have adopted it not to cut costs, but to increase product value. SMT's value lies in its ability to reduce the size and weight of products, produce items - such as hearing aids - not otherwise producible, increase the functional capabilities for the same board space, reduce electrical interference, allow higher-speed circuits, and lower total system cost by reducing product lifetime service costs, when the technology is used in modular manufacturing approaches.

Given that the advantage of SMT lies principally in providing more features to the end-user, it is not surprising that SMT is spreading so fast. It seems inevitable that SMT will soon dominate the industry.

In developed countries, a widespread move to SMT has occurred. Predictions vary, but it is widely expected that, in the next decade, over two-thirds of boards produced will be based on SMT. However, even sophisticated developed country users are taking a number of years to successfully travel down the new learning curve (See Box 6.2).

Firms in newly industrializing economies are taking a "wait-and-see" attitude. They are waiting for many of the bugs in the manufacturing process to be ironed out by more advanced firms and for greater standardization in process parameters and components. In the meantime, they are undertaking some of their own learning by producing, through subsidiaries, specific SMT-compatible components and by developing pilot (or experimental) lines for SMT assembly.

For most less developed countries SMT is still a very advanced technology, requiring access to special components, higher production skills, and higher testing skills.

As SMT comes to dominate through-hole technology economically (providing more features at comparable cost), many products that use through-hole technology will become obsolete. The implications for developing countries are serious. While some of the learning they have acquired in assembling through-hole boards will be transferred to SMT processing, they will need additional education. The new learning will not only include process learning but may also involve developing relationships with different customers and a different set of equipment and component suppliers. In addition, once the excess labor is taken off the production lines, the technology will be more physical and human capital intensive.

6.6 Design for Manufacture

Finally, we consider a more revolutionary change referred to as design-for-manufacture (DFM), which requires a complete reorientation of the design and manufacturing process. The human and organizational costs of such reorientation can be significant; however, the cost savings and increased flexibility obtained are truly remarkable (Rosenthal and Tatikonda, 1990, 1991).

In design for manufacture, the organization focuses on developing producible products, products that take less time to manufacture, use existing or only slightly modified manufacturing equipment, and are designed so that they can be readily tested and repaired. Simplification is the rule, and products are designed with the minimal number of different part types; where possible, existing part types are used, rather than developing new ones. Such reductions in "part proliferation" reduce the cost of individual parts, because fewer different types are needed, and those that are, are bought in volume. The time and money that go into purchasing, logistics and inventory control often decline dramatically. Because the product is easier to make, there are fewer defects and lower repair and scrap rates, and total production capacity may increase substantially (See Box 6.3).

To analyze the impact of a DFM approach on a DC-SMT manufacturer of printed circuit boards, we made several changes to the DC-SMT benchmark model.

First, we modified several parameters to represent a reduction in part proliferation, with its corresponding economies. We reduced inventory storage times for parts and printed wire boards, as a reflection of more efficient and timely materials receipts and ordering structures. The biggest reduction occurred in raw materials inventory storage - for PWBs, from one-eighth of a year to one-twelfth, and for electronic components, from three months to one. In addition, we reduced materials costs to reflect the lower cost of parts, and reduced employment by one manager due to the decrease in purchasing and other manufacturing planning and control tasks.

Secondly, we changed other parameters to reflect the improved producibility and higher quality of the PCB with DFM. We reduced repair rates, scrap rates and actual product repair times by 50 percent. We also reduced machine and workstation setup times by 20 percent, and operation run times by 30 percent. In addition, we combined two manual insertion operations into one, reflecting the DFM approach that consolidates and thus reduces assembly tasks. This eliminated one setup time and slightly reduced individual part run time.

Box 6.3: IN DFM, SIMPLICITY AND DIALOGUE ARE KEY

The costs of complex new products can be high and hidden. While design activity by itself accounts for a relatively small percentage of a product's total cost, it determines a huge proportion of producing, testing and servicing costs. Given the availability of CAE and CAD tools, it is all too easy for firms to design a paragon that is horrendously expensive and time-consuming to manufacture. DFM is a movement designed to prevent such embarrassment and hence yields significant savings in product development and manufacturing costs.

The DFM philosophy emphasizes that product design should be simple and modular, the number of components should be limited to the minimum possible and the design should be reusable for developing new product releases or other products.

It should be obvious that DFM not only offers lower costs, it also allows firms to aggressively introduce new products. Ultimately, it is the mastery of DFM in rapidly designing new products or product variants that will provide the more enduring competitive advantage rather than its cost reducing features.

Conventional wisdom calls for telescoping a series of feature improvements into a single product release. A strategy gaining favor recommends going to market quickly with a limited set of improvements and then building in additional features over subsequent product releases. In electronics, as elsewhere, time is money; companies that get to market first with a new or improved product tend to dominate the market or, at the very least, enjoy large profit margins before competitors force them to trim prices. DFM is ideally suited to this rapid product change strategy. Modular design makes it easy to add or drop features as products and customers change. Common components render changes in the manufacturing process simple and quick.

Coordinating the design and manufacturing functions may require a basic rethinking by management. Some companies give manufacturing engineers veto power over new designs; the drawback to this approach is that it tends to prevent fruitful give-and-take between the two departments. Other companies use "integrators," people who serve a liaisons from the designers to the manufacturing engineers, but this approach puts extraordinary responsibility on a few critical individuals.

Yet another approach is the cross-functional team, consisting of a designer, a manufacturing engineer and perhaps people from test engineering, purchasing and marketing. Experts cite the case of a process-control company that had become interested in producibility after it introduced automated assembly. When automation proved extremely cost-effective, the team set a goal of using autoinsertable components 97 percent of the time. Finally, the approach that involves the greatest degree of structural change entails creating a single department responsible for both product and process.

These approaches to so-called simultaneous engineering do not provide a free lunch. More time is needed from engineers and designers. The shift in organizational arrangements themselves impose a cost, as we have discussed in the case of JIT

Source: Harvard Business Review, Jan-Feb. 1989.

Finally, we made modifications to reflect the simplification and greater reliability in the organization overall that is permitted by DFM. This included doubling, to four days, the mean time to failure of a workstation, and improving labor and machine utilization.

The consequences of all these changes are shown in Table 6.3. The DC-SMT-DFM cost per board is $46 (approximately 33%) less than the benchmark DC-SMT case. Almost half the cost decline comes in the form of lower labor costs as the assembly process is greatly simplified. Labor accounts for nearly one-third of costs in the DC benchmark factory. DFM, therefore, is a further movement towards lowering the labor content of production. The other major savings occurs in materials and scrap reduction.

Table 6.3: DESIGN-FOR-MANUFACTURE IN A DC-SMT FACTORY

Cost Category	Benchmark	"Future Best Practice" (FBP)	Design for Manufacture (DFM)
Material	65.70	65.70	59.13
Direct Labor	22.95	18.53	15.51
Direct Equipment	15.66	12.91	11.38
Non-prod. Direct Labor	9.59	7.70	5.50
Non-prod. Direct Equip.	8.75	7.54	4.90
Indirect Labor	17.95	12.97	9.07
Land Buildings	0.88	0.77	0.43
Administrative	1.14	1.17	0.60
Inventory and WIP	2.66	0.93	1.12
Valued Scrap	8.30	3.15	2.15
TOTAL	153.58	131.36	109.79

An interesting implication of this scenario is that DFM leads to even better cost results than the combined effects of just-in-time practices (the scenario referred to above as "Future Best Practice"). The lesson here is that JIT often deals with symptoms of the manufacturing process without fundamentally changing the process; DFM fundamentally changes the manufacturing process. Specifically, DFM reduces the cost of purchased parts and, by combining some operations and cutting repair time, also reduces the need for labor and equipment. It should be noted though that DFM does not completely substitute for JIT. If certain JIT-based quality control and inventory management practices were introduced into a DFM-based manufacturing process, costs would further decline.

The introduction of DFM in a DC-SMT factory makes it competitive with an NIE-SMT factory (which has benchmark costs per board of $115 and Future-Best-Practice costs of $107). Of course, NIE factories will not be far behind in imitating DFM products and processes. However, the importance of DFM lies in the fact that, for the first time in a number of decades, a DC firm that can stay one step ahead of an NIE firm in product design will enjoy a product advantage with little or no cost disadvantage, shifting market shares in favor of DCs.

Conclusion

The benefits of these emerging technologies will undoubtedly flow to NIEs, and even to LDCs. However, an increasing premium will be placed on human capital and physical infrastructure.

The principal economic impact will be felt through the much higher human capital requirements in these emerging technologies. In SMT, we emphasized that process learning of a substantial nature is occurring at present. This requires engineering skills, and LDCs are likely to be at a disadvantage during the learning phase. Once the process matures, LDCs will, most likely, obtain the lessons of the learning phase at a cost much lower than that incurred by the pioneers. Even so, the learning requirements are likely to be substantially greater than in the case of through-hole technology since SMT is more complex, requires a greater variety of processing skills, and is more unforgiving when errors are made.

Similarly, the gains from DFM will accrue to LDCs as they "reverse engineer" products based on DFM. The very simplicity of DFM should make it easier to imitate. The more fundamental lesson of DFM, however, is that the value addition is shifting increasingly towards the design phase, which is very intensive in human capital. It is possible that DC firms exploiting locational economies may choose to focus on design and farm out the simpler manufacturing process to lower wage countries. However, since DFM will necessarily be accompanied by production flexibility and quick response, the lower wage countries most likely to benefit from such a process will be those with excellent physical infrastructure and long-term marketing and supply links with DCs.

7. CONCLUSIONS

Even in a relatively mature industry, the potential exists for substantial differences in the use of productive resources. These differences can overwhelm any advantage accruing from low input (e.g., wage) costs. As our snap-shots, or scenarios, showed, technical change (occurring in both "soft" practices and "hard" equipment) can easily magnify initial productivity differences if speeds of adoption vary.

We should reemphasize that our scenarios of new technologies were meant to depict engineering practice that is considered well within reach, now or in the next five years. As such, the range of productivity differences depicted here should be considered within the realm of current possibilities. Towards the end we took the liberty of examining more speculative, "blue-sky", scenarios which, if they come about, could create further productivity gaps.

A central implication of this study, therefore, is that factors that impede the diffusion of knowledge are likely to have a powerful effect on international competitive ability. As the speed of change and the knowledge-intensity of production increase, the effects of differences in knowledge will become more potent.

From the perspective of this report, knowledge absorption is impeded by inadequate human capital, organizational inertia, and deficiencies in infrastructure (including networks of supplies and sources of marketing and production information).

One conclusion of our study could be that the knowledge content of even mature, traditionally "labor-intensive" sectors is so high that many low-wage countries have no real comparative advantage in these sectors. An alternative, more positive, view is that efforts directed at creating a broad knowledge infrastructure could have a major pay-off. The example of coastal areas of China discussed in this and companion reports indicates the importance of actively seeking foreign sources of knowledge in any such strategy. Below we discuss some general policy initiatives, but first, we summarize our more detailed results.

7.1 Competitiveness in PCB Assembly

In less than two decades, a highly labor-intensive activity that was projected to move inevitably to low-wage countries has substantially transformed itself. The comparative advantage of high-wage countries with superior human capital and infrastructure (including links with equipment and component suppliers) has risen through a conscious process initiated by firms in these countries. Not only Japan, which had been losing its dominant position in international electronics markets, but also the United States have regained ground in recent years.

We found that NIE firms currently assemble PCBs at the lowest cost, but their competitive edge is being diminished. NIE advantage has resulted from a combination of low wages and high labor productivity.

Productivity has been high because workers are well educated, but also (and this was our main emphasis) because firms have made systematic efforts towards greater organizational efficiency. This has implied instituting programs to reduce inventories and material waste through small but continual changes in the running of the factory. Adoption of quality control techniques, training of workers, and delegating greater responsibility to workers have been the key factors aiding the incremental learning process.

LDC firms with low wages but gross inefficiencies in production just cannot compete on international markets. Even in a relatively mature industry such as PCB assembly, the role of human capital in conducting a process of continual learning is central. Lacking high quality human capital capable of undertaking such learning, LDCs are faced with high unit costs of production. The main message of this study is that LDC firms will need to undertake substantial investment in developing human capabilities if they are to compete in international markets.

Our conclusions on the prospects of LDCs are bolstered by the observation that the two LDC regions increasing their presence on world markets are the coastal provinces of China and the maquiladora area of Mexico. In both cases, the missing human organizational and learning skills are being provided by international firms well experienced in conducting shop-floor learning. It is also relevant to note that, while these regions are specializing in low quality and low complexity products, they are quickly upgrading to higher quality products. The volume (and possibly the share) of products going to more discriminating end-users is increasing in both regions.

At the other end of the wage spectrum, a great many U.S. firms have invested heavily in developing human and organizational capital. Training programs of varying duration, covering the range from shop-floor skills and statistical process control to motivation and organizational skills, are not uncommon. The most dynamic companies (or plants) have introduced integrated programs for training, creating quality circles, delayering the hierarchy, and developing close coordinated relationships with suppliers and buyers. All of these programs improve generation, flow, and use of information.1/

While investment in human capital has dominated the strategies of successful firms, there is little question that tremendous changes are occurring in the physical dimension of the production process. The growth of SMT, the small size of SMT components and the greater precision required in placing them makes automation essential for all but the simplest products. Great improvements are being made in machinery that places SMT components on

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1/ Our assessment in this regard is supported by a study comparing the priorities of U.S., European and Japanese firms. The study states that the main priorities of U.S. firms are: linking manufacturing to business strategies, giving workers broader tasks and more responsibilities, statistical process control, worker and supervisor training, and interfunctional work teams (see Miller and Associates 1990).

PCBs, driving the economics of PCB assembly inevitably towards almost total dominance by SMT.

While automation is spreading rapidly, the role of "softer" techniques as a complement to automation is bound to continue. One example discussed in this report was "design-for-manufacturing" (DFM), a set of techniques aimed at reducing the time from design to commercial manufacturing. The spread of DFM and other such techniques that create cross-functional teams is a response to competition focussing more and more on product differentiation, quality attributes, and being first to the market.

If we look into the future, successful LDC firms will be those that master fundamental production planning and control. In parallel, they will work to improve production quality, by raising the level of workers' skills and increasing the quality of materials and process. Having done that, our unit cost estimates clearly show that these firms would move to automated through-hole manufacture. SMT assembly will also become an integral part of PCB assembly in LDCs as product evolution occurs in that direction.

DCs will work to cut costs on all fronts: inventory reduction, better manufacturing planning and control, overheads (through greater span of control, management reorganization, etc.). To overcome intrinsically high costs, they will seek to increase value by providing state-of-the-art products with the highest function. To increase product value, they will need to learn about and experiment with frontier technologies. They will also need to redesign products to cut costs dramatically and increase product functionality and value. The "design for manufacture" approach that makes products more readily producible and also reduces unit costs will diffuse widely.

NIEs will seek further reductions in product costs through increased process efficiency and, product redesign. As labor costs and currency values increase, NIEs may need to increase the value of product through higher functionality, smaller size, etc. This will mandate adoption of SMT. With their vast experience in learning new processes, the adoption of SMT and increasing levels of automation in design and production should not pose serious problems to NIE firms.

7.2 Policy Implications

The main thesis of this report has been that continuous learning to assemble PCBs is a key component of success in international markets. We have also argued that such learning has occurred faster in the NIEs than elsewhere. The question may be asked: why do the natural forces of competition not induce learning more widely, particularly since much investment in hardware often is not required? Surely, the argument would go, firms competing for survival would see what is best for them and make the necessary changes.

Rarely can the required changes be quickly implemented. Western firms seeking quick fixes to compete against the Japanese have realized this truth rather painfully. The interdependent nature of the integrated manufacturing process raises a paradox. Learning inside the firm proceeds in small steps. However, to make learning possible, discrete changes need to occur inside the firm and in its environment.

An analogy is of help. For a firm to move from its conventional system of manufacturing with large internal and external buffers supporting the process to a new system in which such buffers disappear is akin to, but much wider-reaching than, an organizational shift from IBM PCs to Apple computers. Just as the latter shift requires file translations, new training and new methods of networking, a shift to integrated manufacturing requires new methods and procedures of documentation, new individual and group skills, new plant lay-out and new relations with buyers and suppliers. Such changes are extremely disruptive and impose high short-term costs on the organization. Besides direct costs of new software and training, indirect costs of lost production add up to substantial sums. Many firms have suffered large financial losses in the process of transition.

A central proposition of this study has been that learning is occurring increasingly through systematic techniques. While learning is a process of experimentation, the experiments themselves are conducted in well organized ways using tested tools and techniques. There are a few key reasons why these techniques are not widespread despite their proven efficacy. These relate to organizational and infrastructural inertia.

Thus the shift to integrated manufacturing within a firm must be supported by wider environmental changes that reduce the inertia. Better educated workers, reliable and inexpensive transportation and communication, and industrial extension services are all elements of a support system.

The success of NIEs and, more recently, of China, must be seen in this context (see also Appendix on China). It should be remembered here that when we talk of China, we are referring principally to the regions on the east coast that have specialized in exporting. The four factors that have supported competitive exports are:

- long-term relationships with buyers
- investment in training
- development of communication and transportation infrastructure.
- institutional infrastructure (including support services and local specialized supplier networks).

While these are closely related and reinforce each other, historical evidence from East Asia suggests that they may come partly in sequence (Rhee, Ross-Larson and Pursell 1984).

Long-term relationships with buyers serve a number of important functions. They provide the information necessary to make the manufacturing changes. More importantly for the present discussion, they allow for the leeway in time and resources to tide the firm over the period of disruptive organizational changes. East Asian NIEs built such links with Western buyers. China has had the benefit of links with Hong Kong and Taiwanese firms.

Long-term links with buyers are only one way to achieve these goals. The central theme here is the need to be tied into the best international information networks and mechanisms that support organizational change within the firm. Singapore has relied more heavily than others on foreign investment for this purpose. All East Asian countries have extensive and effective industrial extension services and credit schemes that finance recommended improvements.

Training has been a major focus of international alliances and domestic extension efforts. A Taiwanese or Hong Kong firm that starts sourcing shoes, clothes, bicycles or electronics products from China typically invests substantially in training. Such training is not evident in a specific training budget. The Taiwanese (more so than the Hong Kong) firm locates half-a-dozen or more supervisors each with as much as 15 to 20 years of experience in the Chinese firms. These supervisors stay in the Chinese firms as long as two years even when only simple products involving repetitive tasks, such as shoes and garments are being produced.

In addition to close international links, firms need an enabling environment in which training can be provided, organizational changes can be made, materials with consistent quality are readily available, and investments in learning processes that result in temporary losses represent a reasonable risk. Establishing such an environment requires changes in laws and regulations that place certain restrictions on firms when conducting their business.

Investment in infrastructure is another critical area for public policy. Asian NIEs have set very high standards in this regard. The scale and efficiency of Singapore's port are well known. In telecommunications, all Asian NIEs have taken advantage of new technologies and leapfrogged to the most modern equipment ahead of Western nations (Mody and Sherman, 1990).

A more general point is that any artificial barriers to the movement of information or goods and services will have seriously hinder the ability of firms to organize their internal affairs efficiently. Lengthy import procedures or restrictions on location of production create the need to invest in buffer mechanisms which sharply reduce the capability and the incentives to reorganize for greater efficiency.

APPENDIX A: FRONTIER TECHNOLOGIES

Electronics assembly technology is constantly changing, as researchers seek ever-smaller and more efficient circuit boards - with the ultimate goal of doing away with the boards altogether.

There is a variety of SMT-related technologies, including tape-automated bonding (TAB), chip-on-board (COB), chip-and wire, bare chip mounting and flip chips. In these technologies, a silicon chip, called a die, is directly attached to the printed circuit board surface with a piece of tape. Currently, for both the through-hole technology and the vast majority of surface mount components, the die is first packaged into a carrier and then placed on the PCB.

Doing away with the packaging leads to further miniaturization. The TAB and other similar technologies also reduce processing time and costs. However, the components themselves are costly and not completely reliable.

Hybrid circuits describe a wide range of circuits built from integrated circuit (IC) silicon dies and other components attached directly to a small plastic substrate by various bonding methods; they can be placed very close together, and may have direct electrical connections. This substrate is then attached to the PCB by SMT or through-hole technology. Hybrids are dense, highly reliable packages that take less space on the PCB than if each component were independently attached.

Hybrids can be expensive, and production yields are often low. Most are custom-made devices, used when volumes are not large enough to justify full-custom ICs.

Application-specific integrated circuits (ASICs) are fully custom-designed, high-performance, integrated circuit chips. An ASIC can functionally replace many or all of the components on a standard PCB. The advantage of ASIC is that one chip, which replaces many individual components, requires far less product space, reduces assembly time and increases reliability. However, ASICs have long design and production lead times, and their high development costs limit their use to high-volume or high-value products. It is likely that ASICs will be used more widely as design and production techniques improve.

Thick film technology involves the silk-screen printing of conductors, resistors and insulators directly onto substrates. Screened components, which replace discrete, individually placed components, can be applied quickly, are inexpensive and leave vertical space for other components. Currently, thick films are used on PCBs that also have SMT components. But as the technology improves, both through-hole and SMT component placement may be replaced with multiple silk-screening processes.

The three-dimensional PCB (3-D PCB) is another new electronic assembly technology. Unlike the traditional flat PCB, the 3-D PCB may have several "walls," attached to a "floor," thus creating numerous surfaces for components. These boards can be made with recesses and supports to help hold components and facilitate component assembly. In a product such as a stereo unit, a 3-D board may also serve as the chassis. Connectors that might have been attached to a two-dimensional board can be made an integral part of the 3D board.

These boards are not made of the traditional epoxy base, but are produced by injecting thermoplastic material, a plastic that may be conveniently melted and reformed, into molds; the boards are accordingly called molded printed circuit boards (MPCBs) or extruded printed circuit boards (EPCBs). After the board is molded, copper wiring is attached to the surfaces by a number of traditional or proprietary techniques.

The great advantages of 3-D boards are that they can combine the mechanical and electronic roles of the product in a single unit, and individual boards can be produced at lower cost, using cheaper materials and fewer processes. They also accommodate high component density. However, these and other advantages are offset by the high costs for mold design and manufacture, combined with problems testing and repairing these boards. Traditional testing equipment and methods cannot be used, and it can be very difficult to "reach" approach test points on or within the boards. In addition, the boards may require more storage space than flat PCBs.

Flexible PCBs, which use both through-hole and SMT components, have been in existence for some time, but have become popular only recently. These non-rigid boards can be rolled, placed against uneven product walls, or stuffed into small spaces. Increasingly important are thin-films and opto-electronic capabilities, which use optical fibers rather than copper wiring as signal conductors within a circuit board or individual components.

On the farthest edge of the electronics assembly frontier are bio-chips, which employ biological entities to perform logic and control function needs currently met by electronic components. It is thought that silicon component miniaturization may meet an upper bound by the year 2010, about the same time that viable bio-chips are expected to reach the market.

Electronic assembly technology is dynamic and constantly improving. Leading-edge electronics producers will not employ just one technology, such as SMT, but will leverage a mix of technologies, such as SMT and ASICs on flexible PCBs, to meet various product design objectives.

APPENDIX B: CHINA AND MEXICO EMERGE AS ELECTRONICS GIANTS

B.1 Chinese Electronics Needs Better Infrastructure

The biggest manufacturer of television sets in the world is not Taiwan or Japan or Mexico, but China. In 1989, according to the State Statistics Bureau in Beijing, Chinese factories produced 27 million sets, including some 9.4 million color TVs. Most of it went for internal consumption; only 3.9 million TVs were exported -although, with domestic demand slumping, that balance may radically change.

Such statistics suggest the potential for an enormous consumer electronics industry in China. The Chinese Ministry of Machinery and Electronics Industries has estimated that, in the next decade, the demand for consumer electronics products would quadruple, from $6.8 billion to $27.4 billion. Demand for industrial electronics, computers, and communication equipment is likely to grow at an even faster rate.

The Tiananmen Square uprising in June 1989 and the country's austerity plan put a damper on domestic demand and foreign investment. But that is probably temporary. And well before then, many leading electronics companies based in developed countries were already deeply committed in China.

Many have invested in factories, often as joint ventures. They include Xerox (copier machines), Wang Laboratories (minicomputer assembly), Foxboro Co. (process-control systems), Hewlett-Packard (desktop computers and laboratory instruments). Other blue-chip companies include Matshushita, Philips, Hitachi, JVC, Thomson, Toshiba and Tandy. Possibly more importantly, entrepreneurs from Hong Kong and Taiwan have a sizable presence in the coastal provinces.

The Chinese have sought to foster the presence of such companies through special enterprise zones (SEZs). In the Shenzen SEZ, for example, 43 percent of total annual output of $1.37 billion in 1989 was electronic products. Most of the output comes from one conglomerate, the Shenzhen Electronic Group, established in 1985 by the municipal government to coordinate and manage the army of electronics companies that had sprung up there. The group consists of more than 150 companies, including a number of joint ventures with foreign or domestic concerns. Among them is a joint venture with Japan's Sanyo Corporation, making 1,200 color television sets daily, as well as stereo cassette radios.

In and around the SEZs, relatively anonymous Hong Kong and Taiwan based companies have provided the real fillip to the economy. They have brought modern management methods and technologies to China on a scale that probably dwarfs the contributions of the more renowned Japanese and U.S. companies. One Hong Kong producer that we visited in mid-1991 was producing computer peripherals using extremely sophisticated technologies. A modern SMT production line was among the surprises of the visit. Much effort is being made to train workers and modern marketing and planning skills are being diffused to the local managers. A television producer in Xiamen (the special economic zone in Fujian province) has seen its exports rise to 600,000 sets a year. At the peak, 45 Hong Kong personnel were involved in management in supervision; that number is now down to 20 persons. The factory is now run by a mainland Chinese manager (with a post-doctoral qualification from the United States) and maintains high standards of worker training and quality control.

Many of these companies find, however, that the infrastructure to support the production of computer chips and electronics systems does not yet exist. For example, it is often hard to find consistently good, reasonably-priced parts for electronic assembly. Matching supply with demand is a chronic problem. (That is also the case for China's many manufacturers of television sets; last year, while there was a large surplus of TV sets, China was losing hard-earned foreign exchange on the purchase of imported videocassette recorders.)

Thus, although the government has sought to discourage the import of electronics components, many of the companies are forced to purchase widely from abroad. For the Sanyo joint venture, for example, many of the components-picture tubes, circuit boards, semiconductors - come from Japan, while tuners are purchased from Malaysia and wire from Taiwan. Similarly, an integrated circuit manufacturer buys chips from South Korea - through Hong Kong - and Taiwan. However, many foreign manufacturers say they expect to purchase a steadily-growing percentage of their components locally in the next several years.

Software production is a very rapidly growing area. Chinese skills (residing in its various technical institutes and universities) are being tapped by most major international computer and software companies through the establishment of joint ventures. The principal market being targetted is Japan and, for that reason, Japanese firms have been most active in establishing software ventures. Many of these ventures are located in Shenzen, but Shanghai, Beijing and other major cities on the east coast have also attracted investors. Exports of software are yet small but are likely to major growth industry.

Software development is only one example of a general move to products with higher sophistication. Chinese authorities are actively promoting higher value-added and higher quality production not only in electronics but almost across the board. In electronics, video-cassette-recorders and compact disc players are apparently receiving special financing and other incentives. In addition, support services in the form technology diffusion institutions and industry-university links are being established. The history of such support services in China has not been good; but neither has China been regarded as a major manufacturing base for world markets.

Production for the domestic and export markets has been relatively dissociated in the recent past. Exporters do sell some of their output domestically but the vast majority of domestically oriented producers export very little. The Chinese government is currently engaged in restructuring its major enterprises in order to make them more competitive. Their entry into world markets could have a significant impact on international market shares.

B.2 Forces Shaping Mexican Electronics

Mexico, whose cheap, unskilled labor was originally the attraction for foreign manufacturers, is becoming the site of increasingly sophisticated production in electronics. IBM has a state-of-the-art microcomputer factory in Guadalajara. Hewlett-Packard, which has a minicomputer factory there, is exporting more than $75.5 million of equipment from its various Mexican facilities. Adelantos de Tecnologia, a joint venture between the United States company SCI (North America's largest contract manufacturer in electronics) and a Mexican group, Elamex, manufactures printed circuit boards for IBM, Hewlett-Packard and Standard Microsystems. It recently opened an advanced facility using surface mount technology.

Admittedly, Mexico's electronics industry is still relatively small. Sales of computer products represent less than 1 percent of gross national product, compared with 3.4 percent in the U.S. and 2.1 percent in Japan. But computer production has grown from $171.1 million in 1985 to $497 million in 1988, and the pace should continue under a government program aimed at extending computer usage within Mexico as well as increasing sales abroad.

Initially, Mexico's entry into electronics was as the lowest-cost producer, and that remains a powerful attraction for manufacturers in developed countries. The country has traditionally specialized in the production of passive components, such as connectors and capacitors, and roughly half of its electrical and electronic exports to the United States are component fabrications and board assemblies. Thousands of Mexicans are employed in board assembly for U.S. manufacturers.

Most of them work at the **maquiladoras**, the approximately 1,800 in-bond factories on the Mexico-U.S. border. Under a program established in 1965, U.S.-based companies are allowed to export finished goods back to the U.S. and pay duty only on the value-added. Increasingly, Japanese companies have been drawn by this ploy. As a result, the **maquiladora** zone is home to the assembly facilities of most of the world's major electronics companies, including Matsushita, Sony, Sanyo, Toshiba, Hitachi and Samsung as well as the likes of RCA and Zenith. One of the earliest, Zenith is still the largest employer, with some 14,000 workers - about 45 percent of the people working in the 15 or so consumer electronics plants in the border zone.

In fact, the **maquiladoras** are one of the biggest television production centers in the world. And their success in television and consumer electronics may bring new customers. General Dynamics Corp. recently announced plans to open a plant in Tijuana that would employ 200 workers to make electrical components for its defense contracts.[1/]

1/ Electronics is not the only industry for the **maquiladoras**, whose activities range from assembling clothing to stuffing mail into envelopes. In 1989, the total industry employed nearly 500,000 workers - 17 percent of all manufacturing employment in Mexico - and earned the country nearly $3 billion in foreign exchange.

But with automation and SMT making manual board assembly increasingly obsolete and PCB production less labor-intensive, Mexico is being forced to become a world-class producer. In fact, problems in the workforce - so severe that, in the case of one electronics plant in Juarez, scrap costs reportedly exceeded labor costs - have compelled some manufacturers to automate. The introduction of more sophisticated and complex manufacturing technology has necessitated more training.

Accordingly, the Mexican government is working with foreign manufacturers to make its workforce competitive with those of developed countries and newly industrializing economies. The government requires a one- or two-year employee-training program from any foreign company wishing to locate in Mexico.

Meanwhile, a number of foreign manufacturers are trying to upgrade the quality of engineers and senior-level technicians. IBM has invested heavily in projects like postgraduate education in electrical engineering at the University of Guadalajara and advanced computing and software development at institutes in Guadalajara and Mexico City. Other organizations are helping fund CAD/CAM laboratories in institutes of higher education in Monterrey, Mexico City and Puebla.

APPENDIX C: MODELING THE FACTORIES

An overview of the way a factory's operation can affect its performance is useful in understanding the modeling approach. Discrete manufacturing facilities typically possess complex system dynamics. Multiple products need to move through various types of work centers, and in doing so they compete for resources. Different products have different "cycle times" (the time to complete operations on one piece, also called "run times") at the various work centers. Changing a work center's readiness to work on a product, after it has completed a different type of product, requires a "setup"--which can be much longer than the cycle time itself. Equipment can fail unpredictably. Intermediate products can be below specifications and require rework or may even have to be scrapped altogether.

All of these factors cause delays or consume additional resources, add to the work-in-process (WIP) and material costs, and thus affect the overall capacity and efficiency of the factory. Many of the manufacturing alternatives that are available today aim at ameliorating these factors, and thus it is important to model their effects. Thus, to capture such effects accurately, one needs to construct a model of factory dynamics.

Rather than write from scratch a software package with such a model, we used an available factory modeling package called ManuCost from Network Dynamics Inc. (Burlington, MA).

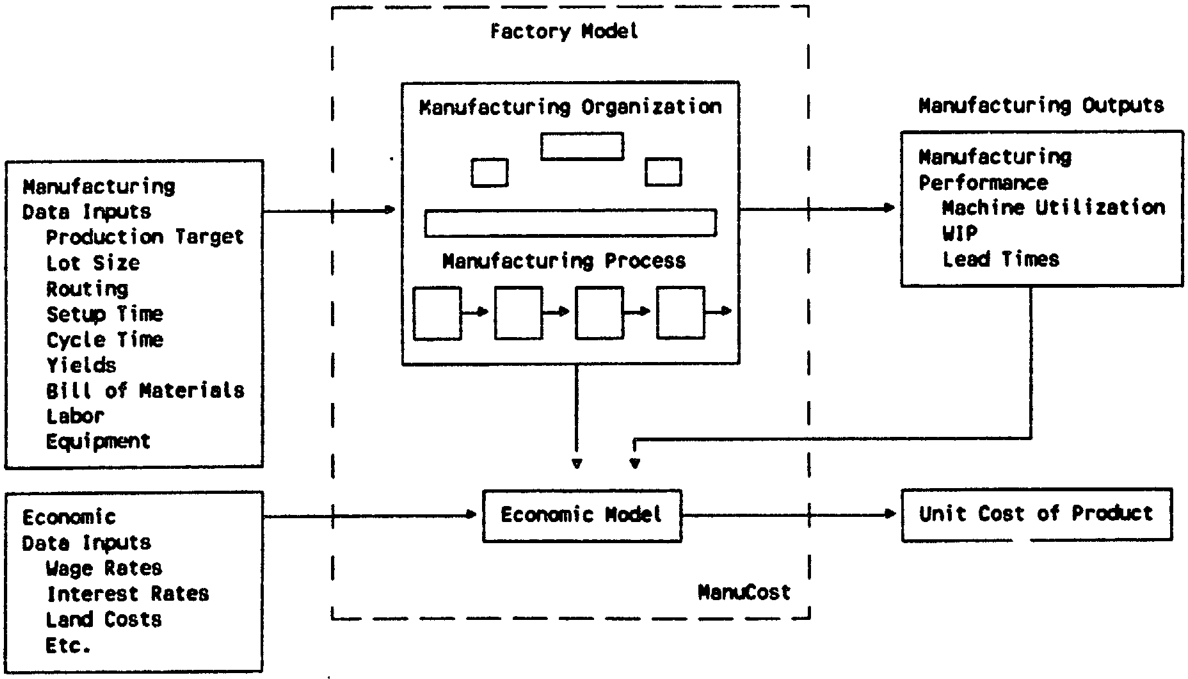

Figure C.1 SCHEMATIC OF THE COST MODEL

This factory modeling software package has a number of features that make it well-suited for our use:

- It allows detailed specification of operations and the links between them. At each operation, the resources used (equipment, labor and materials) are specified. Labor is split by skill category.
- The routings (the sequence of operations required, as well as the equipment on which they must be performed), yields (the proportion of good parts obtained from an operation), rework rates, and set-up and cycle times (defined above) for each operation on each available machine are also specified. If equipment is automated or semi-automated, these times can be separated into those when an operator is needed, and those when the operation can continue unattended.
- The model contains a set of dynamic equations. For given machine reliability rates, variability in arrival of material from one station to another, yields, set-up and cycle times, the equations predict the average utilization of various resources installed in the factory. The model is, therefore, able to estimate performance measures such as total production capacity, work-in-progress (WIP), specific equipment and labor utilization rates, and product lead times (the time it takes for an order to go through the entire factory).
- The package also incorporates an economic model that allows one to specify costs of various direct inputs (such as material, equipment and labor) as well as indirect inputs (such as management salaries and facility costs). It then combines the manufacturing model with the economic model to accumulate costs (including appropriately allocated indirect costs) through the production process, up through components, subassemblies and final products.
- A particularly interesting and important feature of the model is its system of scrap estimating. The model keeps track of scrap through data on yields and rework rates at each operation. The model not only estimates the material value of the scrap, but also keeps track of the value added at earlier stages that goes along with the scrapped material. Similarly, the model's ability to predict the quantity of WIP at each stage of production, leads to an accurate prediction of WIP carrying costs. As we shall see, these costs are important in determining opportunities for improvement.
- The package is based on the Rapid Modeling approach to manufacturing modeling, as distinct from the "discrete-event simulation" approach (e.g. see Suri 1989). Rapid Modeling is less ambitious, but as a consequence also requires less data and allows much faster turnaround for examining alternatives. This package has

been successfully used in manufacturing analysis by firms such as Alcoa, Digital Equipment Corp., IBM, and Siemens.

Note that the model is purely an evaluation tool. No optimization is done, only prediction. Thus if a desired production rate or other performance measure is not achieved, the analyst must decide on what alternative to try, and then modify the inputs accordingly. The performance reports provided by the model usually assist in directing the analyst towards the necessary modification. For example, if a production rate is not achieved, the model will show the bottleneck resource(s). The analyst can then explore various alternatives, the most obvious one being to add more resources.

Furthermore, in the benchmark cases, the set of alternatives may be limited by the observed data in the actual factories. However, in the scenarios for improvement, many other alternatives may be available, such as the use of methods to improve yields, or ways to shorten set-up or cycle times, or the use of new materials or automation. These alternatives require a wide knowledge of manufacturing processes as well as considerable design creativity, and thus render the use of an optimization scheme extremely difficult. Instead we use an iterative approach that allows the analyst to try alternatives until the desired performance indicators are obtained.

Relation to Activity Based Costing (ABC)

New accounting methods for manufacturing, such as Activity Based Costing (ABC), are gaining acceptance (e.g. see Cooper and Kaplan, 1988). While our approach is in the spirit of ABC, there are some important differences. ABC provides accurate cost analysis of existing operations, but would have been less appropriate for our "what-ifs". In most of the scenarios that we undertake, the structure and dynamics of the manufacturing system change in a nontrivial way. For example, new technology (e.g. fixtures and hydraulic clamps that reduce setup time) combined with a new operating approach (smaller lot sizes) can drastically decrease the amount of work-in-progress (WIP). It is important to model the manufacturing dynamics first, in order to predict the new resource utilizations and the new WIP, and then conduct the cost allocation on the outcomes. ABC is designed to do the latter, thus it can only be meaningfully applied to what-ifs that are "in the neighborhood" of the current process structure and system. Our approach predicts the new operating conditions first, and then does the cost analysis. However, both ABC and our methodology share an important attribute: they underscore the need for development of improved costing methods in evaluating manufacturing alternatives.

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