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A backcast methodology for planning and justification of advanced manufacturing technology acquisition: A model of capability building process.

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A Backcast Methodology for Planning and Justification of Advanced Manufacturing Technology Acquisition

-- A Model of Capability Building Process

by

Zheng Liu

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To Whom I Love.

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Abstract

Inadequacies of conventional investment justification methodologies in Advanced Manufacturing Technology (AMT) cases are well known. The inadequacies mainly stem from exclusion of qualitative and "intangible" factors when evaluating AMT investment proposals. To address the problem, a framework of AMT planning and justification is presented in this paper. The framework takes a 'backcast' approach, in which the AMT acquisition is modelled as an essential effort in a process of building manufacturing capabilities for a firm's long term competitiveness positioning. The intangible benefits associated with AMT acquisitions are explicitly considered and modelled as a set of manufacturing capability measures. Non-financial, or activity-based performance measures are adapted. Planning of AMT acquisition is modelled as a "backcast" process consisting of identification of capability upgrading needs, or 'capability gaps', in manufacturing bases, with respect to manufacturing strategic objectives, and selection of appropriate AMT programs to close the gaps. Selection and justification of AMT program alternatives is modelled as a multiple criteria decision making process. Factors of actual concern may be firm-specific. The range of factors considered in this paper includes level of capability upgrade (% of gap closure), demand on strategic resources in terms of financial constraint, implementation time and learning period, and compatibility of AMT candidates to a firm's organizational infrastructure. Quantitative evaluation of subjective factors are attempted by Analytic Hierarchy Process (AHP) and fuzzy set methods. Multiple criteria decision making is modelled by the Compromise Programming approach. The framework enables decision making on AMT investment to be based on integrated programs rather than isolated projects. Implementation of the framework is shown to be based on activity-based performance measures in a firm.

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Nomenclature

<u>Chapter 4 & 5</u>

$G = \{Gi | i=1,2,3,4\}$ = set of generic goals

i= index of goals

$WG = \{wg_1, wg_2, wg_3, wg_4\}$ = priority weight vector of Gi

$OO=\{OO_{ij} | i=1,2,3,4; j=1,2..j(i)\}$ = set of operational objectives

j = index of operational objectives

$WOO=\{woo_{ij} | i=1,2,3,4; j=1,2..j(i)\}$ = weights of OO

$PA=\{PA_{ih} | i=1,2,3,4; h=1,2..h(i)\}$ = performance aspects

h = index of performance aspects

$WPA = \{wpa_{ih}\}$ = weight vector of PA

$FA=\{FAl | l=1,2..7\}$ = major activities

l = index of activities

$WA=\{wa_l | l=1,2,..7\}$ = composite weights of FA

SF={SF1, SF2, SF3} = set of System Factors

$WSF=\{wsf_1, wsf_2, wsf_3\}$ = weights of SF

$T = \{Tk | k=1,2,3,4\}$ = technological factor components (refer to Table 4-1)

k = index of technological components

$WT = \{wt_k | k=1,2,3,4\}$ = priority vector of T

$TEk = \{TEkp | p=1,2,..p(k)\}$ = subcomponents in a technological area Tk

p = index of subcomponents of TEk

$WTE = \{wte_{kp}\}$ = priority matrix of TEk

$ORG = \{ORG_{\epsilon\theta} | \epsilon=1,2,3,4; \theta=1,2,..\theta(\epsilon)\}$ = organizational factors

$\epsilon = 1,2,3,4$ = index of organizational areas

$\theta = 1,2,..\theta(\epsilon)$ = index of subareas in ϵ

$WORG = \{worg_{\epsilon\theta} | \forall\epsilon,\theta\}$ = weights of organizational factors

<u>Chapter 6:</u>

Alt_r = Technological upgrade alternative r.

r = 1,2,3...R, is the number of alternatives.

X_{kp0r} = decision index

$G = \{Gi | i=1,2,3,4\}$ = set of generic manufacturing objectives

$WG = \{wg_i | i=1,2,3,4\}$ = Priority weight vector for G

$PA = \{PA_{ih} | i=1..4; h=1..h(i)\}$
= Performance objectives

$WPA= \{wpa^{(ih)} | \forall i,h\}$ = Priority weights of performance objectives PA_{ih} with respect to Gi,

$T = \{Tk | k=1,2,3,4\}$ = Manufacturing base technological areas

$WT^{(ih)} = \{wt^{(ih)}_k | k=1,2,3,4\}$ = Priority weight vector for Tk with respect to supporting objectives in PA_{ih}

TEK = {TEkp | k=1,2,3,4; p=1,2,3...p(k)}

= Member set of technological area Tk

WTEk = $\{wte^{(ih)}{}_{kp} | p=1,2...p(k),\ k=1,2,3,4\}$

=Weights of tekp contributions with respect to PA_{ih}

$M^{(ih)}{}_r$ =PA_{ih} related performance capability measure of state (program candidate) r, r=0,1,2...u

u denotes the target state, the upper bound, or ultimate level of performance in PA_{ih}

$D^{(ih)}{}_{0r}$ = the Absolute Improvement level in PA_{ih} due to upgrading system from state 0 to r

$d^{(ih)}{}_r$ = the Improvement Rate (%) in PA_{ih} from state 0 to r with respect to the desired upgrading step 0 to u

$C^r{}_0$ = Initial cost ($) of the upgrading program Alt_r.

$E^r{}_n$ = Annual net cash flow ($) in year n, expected from the upgrading program Alt_r

n=1,2..N(r) = life of Alt_r in number of years

MARR = Hurdle rate (%) used by the firm

τ_r = Time to implement Alt_r in the firm, [time]

Ω_r = Learning period after implementing Alt_r, [time]

ORG = $\{ORG_{\epsilon\theta} | \epsilon=1,2,3,4;\ \theta=1,2..\theta(\epsilon)\}$

= Organization Factor elements

$WORG_{\epsilon\theta}$ = "Riskiness to Change" weights of $ORG_{\epsilon\theta}$, $\forall\epsilon,\theta$

$Y=\{Y(ORG_{\epsilon\theta})_r | \forall\epsilon,\theta,r\}$ = Degree of Incompatibility of $ORG_{\epsilon\theta}$ to Alt_r.

Chapter 1.

Introduction

1-1. Fields and motivation for the research:

It was noted that North American industries had a systematic disadvantage compared to their major international competitors like Japan and Germany in capital investment system. Major differences between American, Japanese and German capital investment systems are identified in following aspects:

US	Japan&Germany
*Fluid capital	*Dedicated capital
*Measurable investment return	*Secure corporate position

The country-wise differences in the foci of the capital investment systems were considered the causes for the relative underinvestment in the industries and the subsequent decline in competitiveness. Reforms in the North American capital investment system were advocated, in terms of:

▹ Shift measurement away from solely financial results;

▹ Transform financial control systems into position-based control system--the asset position needed for competitiveness, and investment needed for achieving the position;

▹ Move to universal investment budgeting -- to evaluate investment programs, not just discrete projects [**Porter**, HBR, Sept.1992].

Superior manufacturing capability is the basis for competitiveness positioning. Manufacturing capability is the culmination of continued technological development and organizational learning. Adopting advanced manufacturing technologies (AMT), in the forms of computerized automation and computer integrated manufacturing (CIM), is an essential part in capability building endeavour. However, there were cases where AMT acquisition proposals were rejected for failing the financial justification measures. On the other hand, there were plenty of examples in which expensive AMT acquisition failed to bring in the expected performance gains even when they passed the initial financial screening. AMT adoption, the major form of manufacturing capability development, thus challenges manufacturing firms in two related fronts: planning and justification of AMT implementation. The challenges arise from:

i) Nature of advanced manufacturing technology.

ii) Shift in the paradigm in which AMT is implemented and evaluated.

Definition of AMT Technology: **Noori** and **Radford** [1990] define technology as having three components:

* Hardware -- the physical means of carrying out the tasks to achieve objectives or goals;

* Software -- set of rules, guidelines, algorithms necessary for using the hardware; the know-how;

* Brainware -- the purposes, application, and justification of hardware and software, the know-what and know-why.

As shown in Fig.1.1, The three components are interdependent, and are embedded in a Technology Support Network. The Support Net is a complex network of physical, informational, and socioeconomic relationships which support the proper functioning of a given technology towards the goals.
Distinct from technologies which improve one of the components while preserve the relationships of the existing support network, Advanced Manufacturing Technology (AMT) affects the very structure and organisation of the support network. That is, AMT changes the nature of tasks, ways in which they are done, interconnections, nature of physical and information flows, the skills required, the roles played, the styles of management and coordination, and the organisation structure.

Paradigm Shift: Discussions on paradigm shifts in manufacturing competitiveness are abundant in literature since late 1980s [See, eg., **Noori**, 1991 ; **Sonnenberg**, 1993; **Stalk**, 1993; **Stalk&Webber**, 1993; **Smith et al**, 1991]. The theme is that the old paradigm of low cost-based competition (economy of scale) has shifted to a new paradigm of competing on fast innovation and delivery (economy of scope and speed) while maintaining superior quality and lower costs. This trend is observed by researchers that "What we are witnessing in many

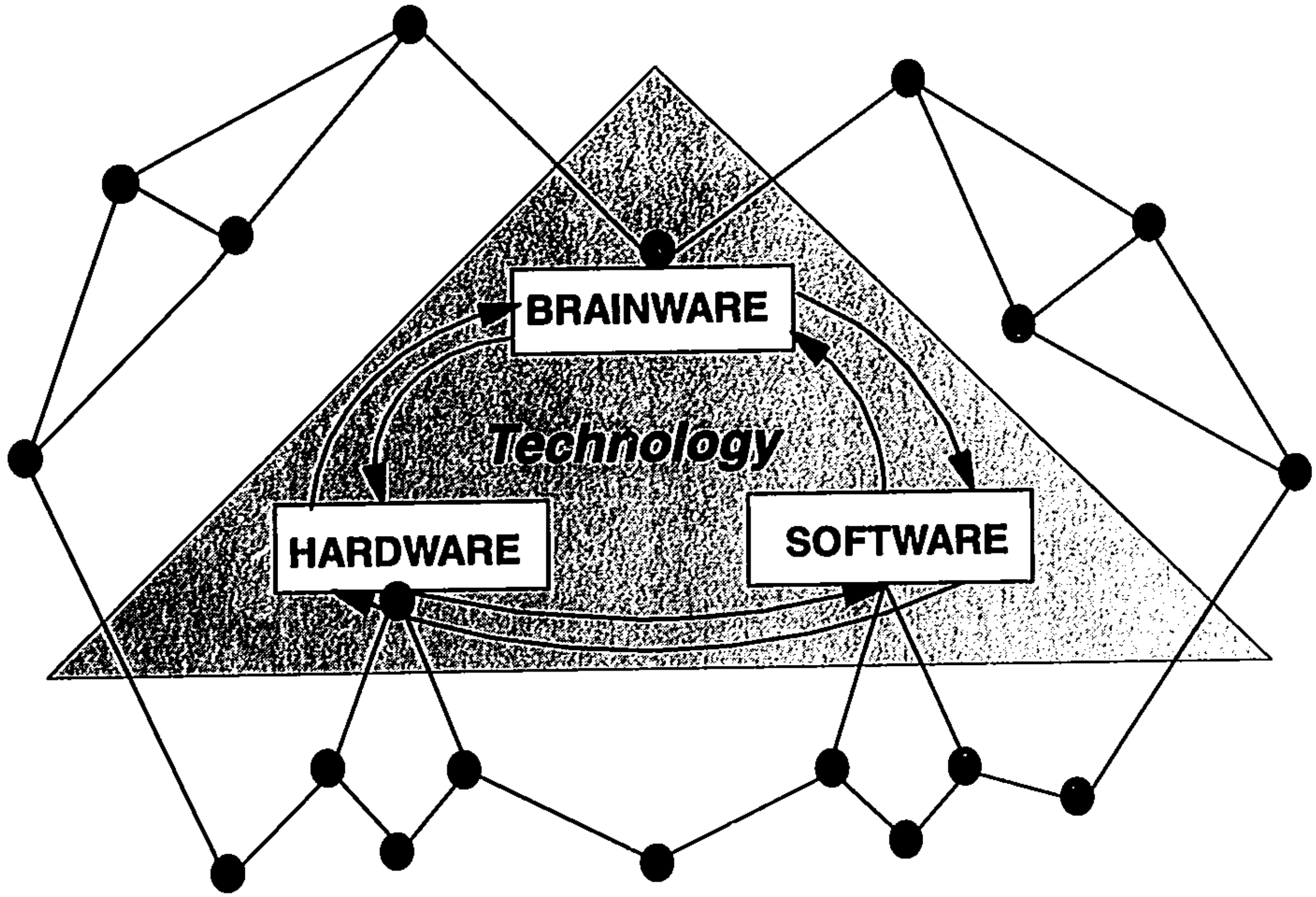


Fig.1-1. Technology and Its Support Net Embedding

manufacturing firms is an attempt to find a way out of the Fordist/mass production paradigm....most efforts to implement computer-integrated technology are taking place as part of the attempt to make this shift in paradigm" [**Smith et al**, 1991].

These concepts lead to the following statements that outline the present research endeavours: First, the conventional investment justification criteria, which are built on tangible factors like cost reduction, lose much of relevance in AMT cases. Instead, the 'intangible' long term benefits such as improvement in quality, increase in flexibility and fast delivery are of greater importance in justifying AMT. Also, the costs associated with AMT acquisition extend beyond capital commitments to include socio-economic and other intangible costs.

Second, AMT investments demand an integrated, or holistic, approach in planning and implementation. AMTs affect every link in the 'value chain' of the firm; the potential benefits of new AMT acquisition are realizable only when the new AMT is compatible with a host firm's technological and organizational infrastructure, or when the required changes in the infrastructure are feasible for given environmental conditions. Therefore, AMT acquisition is not purely a technological or engineering problem, but has wider implications and hence demands an integrated, or holistic, approach in planning and implementation.

While the distinction between the two aspects associated with AMT acquisition is of academic research interest, the task of improving manufacturing capability in any particular firm has to be tackled as a whole. Justification of AMT is but a sub-set of the entire planning process. The inadequacy of conventional justification methods is not so much due to lack of theoretical soundness; DCF methods, for example, have solid foundations [**Kapulan**, 1986]. Rather, their problems are due partly to the segregation of true objectives of AMT acquisition in terms of performance measures and criteria used in justification, and partly to lack of relevant and reliable data of performance gains expected from AMT implementation in a particular environment [**Meredith&Hall**, 1987; **Maskell**, 1991; **Oden**, 1992; **Primrose&Verter**, 1994].

Many attempts have been devoted to remedy the inadequacy of conventional justification methods. Comprehensive surveys on previous research in this field can be found in literature. [**Swamidass&Waller**, 1990; **Proctor&Canada**, 1992; **Canada&Sullivan**, 1989; **Mohanty**, 1993].

Despite the research efforts in these fields, these problems are yet to be solved satisfactorily, and industries still have to rely either heavily on conventional economic justification criteria, or on decision makers' intuition for evaluating AMT proposals [**Jones & Freeman**, 1992]. The difficulties in real-life problem solving stem from their interdisciplinary nature and on their situation dependence. Further, many researches are too academic oriented, with many assumptions difficult for practitioners to substantiate.

A methodological question about AMT justification issues is that AMT is not an objective in itself, but a means to an end. While previous efforts focused on providing techniques for measuring and justifying AMT proposals on the grounds that they may bring in certain benefits, AMT justification tasks may be more meaningfully accomplished by starting with explicit definition of objectives, ie., types and levels of manufacturing capability desired for the future, and then select the AMT alternatives to fill the needs. By this logic, justification is embedded in the strategic planning process for capability build-up, and is reduced to the task of choosing the most appropriate alternative for the defined objectives.

For this strategic planning approach to work, it is critical to define AMT investment objectives as building manufacturing capabilities needed for the future rather than as merely enhancing existing capabilities. [**Hayes & Pisano**, 1994]

To facilitate understanding and implementation of the process, it is necessary to establish a unified framework, in which AMT investments are planned and evaluated as a series of interdependent and integrated programs, and justified by relevant criteria with emphasis on these programs' potential to improve manufacturing capabilities. [**Porter**, 1992; **Hayes&Pisano**, 1994].

Such a framework should include the following dimensions:

--A set of performance measures that captures the tangible as well as 'intangible' aspects of manufacturing system capability;

--A scheme to identify critical areas of manufacturing systems for the purpose of continuous capability improvement;

--A scheme to link AMT programs with manufacturing capability improvement, for the purpose of selecting an appropriate AMT program.

--A method of estimating impact of AMT programs on the organization, and potential barriers, for the purpose of smooth implementation.

The framework can be termed as the strategic planning approach for building manufacturing capabilities. The previous researches related to this approach will be reviewed in the next chapter.

1-2. Statement of Research Objectives

It is the objective of this thesis to develop a methodology that combines AMT planning and justification within a unified framework. In particular, the present research aims to:

1) Establish the conceptual framework wherein the strategic manufacturing objectives, performance capabilities, and AMT acquisition programs are explicitly linked together;
2) Develop a set of integrated performance capability measures that facilitate positioning of a manufacturing system;
3) Develop a scheme to facilitate identification of critical areas of the manufacturing system for capability improvement;
4) Develop an operational methodology to evaluate impacts of AMT programs (upgrading alternatives) on manufacturing capability goals and on infrastructural factors, to facilitate selection of appropriate AMT alternatives.

While small and medium sized manufacturing firms with batch production in machining industry are the intended sectors for application, the methodology shall be general and flexible in handling a broad range of real life situations.

The methodology intends to aid planning and implementation of AMT for upgrading existing capability in manufacturing firms, rather than for creating new manufacturing facilities.

1-3. Organization of the thesis

The materials presented in this thesis are organized around following interconnected clusters:

Literature review and definition of the specific objectives. Issues and problems on justification framework, methodologies, parameter measurements and analysis techniques are reviewed; which leads to identification of the nature and scope of the research problem, and specification of the objectives of the present thesis. Chapter 2 is devoted to this area.

Building the overall conceptual model. This is dealt with in Chapter 3, which discusses: the backcast logic; task modules within the framework; issues on strategic planning process and setting of capability goals; issues on performance capability measurements and implications to the information input/output requirements of the framework.

Refining the building blocks (task modules) of the conceptual framework. Chapter 4 is devoted to this area, which covers the issues on: factors concerned in each task module, their definitions, dimensions, and measurements; hierarchical relations of the factors; techniques for assessing interaction impacts between the factors within the framework.

Further refining the building blocks. Chapter 5 gives a close-up description of the key factors, and details the method of using AHP to analyze the technological bottlenecks.

Synthesis and MCDM. The problem decomposition and analysis lead to the finishing stage of synthesis and decision making. The issues and techniques in this area are addressed in Chapter 6, which discusses: evaluating alternative by capability building objectives for justification purpose; measurement issues of subjective criteria; multi-attribute scaling problems and comparison issues; simultaneous trade-off for multi-criteria decision making.

Illustration and validation of the methodology. These are handled through a case study in Chapter 7 and in Chapter 8. Evaluation of the present methodology and projection for future work are incorporated into the conclusions parts of the thesis in the last chapter.

Chapter 2.

Review of Literature on Strategic Planning and Justification of AMT

2-1. Literature on Classification and Scales of Advanced Manufacturing Systems (AMS)

In this chapter the term AMT and Advanced manufacturing systems (AMS) are used interchangeably. AMS as a broad term encompass the range of automated manufacturing equipment to computer integrated manufacturing systems (CIM). Classification of AMS have been proposed by several researchers, two are cited below for setting the perspective.

Meredith and Hill [1987] proposed a Four-level scale of advanced manufacturing systems, as follows:

Level 1: Stand-alone, hardware that is commonly controlled by self-contained computers, or possibly programmable controllers. Examples are NCs stations, Robots, or other equipment with highly limited local information requirements.

Level 2: Cells, which have a higher level of integration and communication, consist of multiple pieces of individual, Level 1 equipment, placed or connected in a cellular configuration to perform multiple but ordinary tasks on a family of parts.

Examples are group technology lines; FMS comprising half-dozen or so NCs with automated material handling; and computer aided engineering (CAE).

Level 3: Linked Islands, some cells (islands of automation) from the Level 2 are connected to form linked islands, typically through computerized information networks.

Level 4: Full Integration (CIM), links the entire manufacturing function and all its interfaces through extensive information networks. This level includes all level 3 systems, as well as transportation equipment, functional departments, top management and so on.

Lei & Goldhar [1990] proposed a "10-level" system integration:

1) Single islands
2) Multiple similar islands
3) Order entry + manufacturing
4) Design + manufacturing
5) Design +manufacturing +distribution
6) Total operations system+integrating organisation units
7) Operations +business systems
8) Link to customer operations
9) Link to customer BIS +operations
10) Link to customer for design

2-2. Literature on AMT Justification Framework

Meredith & Hill [1987] point out that as ultimate objectives or *"intended use"* for achieving different levels of systems integration differ, evaluation considerations and criteria for justification need also be different, as shown below:

Level of Manufacturing System Technology Integration

	Level1	Level2	Level3	Level4
Purpose	Replace <------------------------------------>Change			
Objective	Efficiency <----------------------------->Effectiveness			
Benefits	Tangible <---------------------------------->Intangible			
Scope of effects	Local <------------------------------------>Systemwide			
Organisational impact	Minimal <----------------------------------->Extensive			
Risk	Slight <---------------------------------->Substantial			

Justification Techniques	Examples	Level1	Level2	Level3	Level4
Economic	-PB -ROI -NPV -Cashflow	++++	+++	++	+
Portfolio	-Programming Models -Scoring Models -Growth Options	____	++++	+++	++
Analytic	-Value analysis -Risk analysis	____	____	++++	+++
Strategic	-Technical importance -Business objectives -Competitive advantage -R&D	____	____	____	++++

(Legends: ---- Largely unnecessary; + Useful; ++++ Most appropriate)

Swamidass and Waller [1990] reviewed the literature in the field of AMT justification upto 1988. They divided the managerial tasks concerning AMT acquisition into two dimensions: planning task, and financial justification task. They then grouped the financial justification techniques into 6 categories:

Financial Justification

(1) DCF	(2) Scoring methods	(3) Cost & benefits analysis	(4) Risk analysis	(5) Computer enhanced analysis	(6) Strategic value of flexibility

There is clear commonality between these two groupings. The distribution of the literature indicated that the planning aspect of AMT acquisition attracted much less attention from the researchers than the financial justification aspects. This imbalance in the emphasis deserves reconsideration because it is an unjustified bias, and will be discussed further.

Proctor and Canada [1992] made a comprehensive review of the research upto 1990, and commented on the evolution of both the conventional (capital budgeting) and non-conventional evaluation and justification techniques. They pointed out that the theoretical models dealing with the less tangible factors of AMT investment were generally based on either "non-traditional" techniques, or traditional DCF techniques with elaborate accounting type measures to encompass the intangible measures, or a combination of the two. They identified the treatment of the "less tangible aspects" to include the following in the justification process:

1) Strategic linkage
2) Competitiveness consideration
3) Quality
4) Flexibility

Their paper contributed to increased awareness and understanding of the theoretical progress in the field rather than to establish a framework for justification.

Another summary review of the field prior to 1989 is from **Mohanty** [1993]. Mohanty states that AMT justification often means economic justification. He classified various justification methods into the following groups:

Qualitative methods	Semi-quantitative methods	Quantitative methods	Decision Support systems (DSS) & Expert systems (ES)
	--LAM	--Eng.Eco	
	--AHP	--Math.Progm	
	--MCQA		

The sources of literature reviewed by Mohanty were quite different from those covered by **Swamidass and Waller** [1990]. Still, there is commonality between the classifications.

The quantitative methods category appears to be the most ploughed field of all, judged by the quantum of available literature. The majority of these papers, however, deal with issues of an operational nature.

Qualitative methods are termed "generative techniques" as these techniques provide insights for making decisions, rather than prescribing the decisions themeselves. Semi-quantitative methods are able to deal with multiple, often conflicting objectives, as well as the non-monetary performance criteria that emerge when the strategic and tactical implications are grouped for justification.

2-3. Literature on Strategic Considerations for AMT Investment

Strategic needs cited as the justification for AMT investment include *competitive positioning, manufacturing capabilities, and learning*. Manufacturing firms who wish to maintain competitive positions in the market place should gear up the entire organisation toward the customer requirements by purposefully building technology/marketing linkage, ie. the capabilities that can be the "order qualifiers" and "order winners" in the competition. The "Order Winners" include such factors as quality, response time, customisation, and price [**Meredith&McTavish**, 1992]. Such capabilities in manufacturing term translate into higher level AMS. The justification for investing in AMS is clearly a matter of survival, not merely of success.

Incremental capability building approaches in AMT integration are advocated. **Hay & Williamson** [1991] proposed a 'Strategic Staircase" planning model, which start from explicitly setting the company's goals in the market place in the future, and then working backward to determine what should be the steps or milestones to reach the goals from the current position. Behind this supply-side strategy lies the concept of sequential development of capabilities, skills and hard and soft assets (such as plants and brands). The sequential efforts will lead to closing a 'capability gap'.

Similarly, **Sharp** [1991] suggests that in justifying high risk investments decision makers should consider, in addition to the cash flow, the OPTIONS that the investment will provide which allow the firm to do something down the line that it wouldn't have been able to do without the previous investment. There are two types of options--incremental options and flexibility options. The values of the options are difficult to quantify, but they tend to increase with the uncertainty and duration of the project.

These suggestions addressed the importance of taking a long term strategic view in evaluating AMS investment, they provide a general guidance that support the "gut feel" of management judgement. Industry management, however, needs more solid and systematic methods in justifying AMT, especially when the scope of effect are multi-departmental and involves both internal and external stakeholders.

2-4. Literature on AMT Decision Support Systems

The decision support system (DSS) and expert systems (ES) in the area of AMT planning and justification are attracting increasing attention. Recent literature about DSS include **Son** [1991a]; **Stam & Kuula** [1991]; **Suresh** [1990]; **Mohanty** [1993].

Son developed a DSS for factory automation (DSSFA), which is basically an Economic justification model with consideration of intangible factors. The intangibles included in Son's model are manufacturing flexibility (measured by set-up, waiting, idle and inventory costs) and quality (measured by preventative and failure costs). Therefore the model is mainly for the tactical purpose of selecting alternative Factory Automation (FA) configurations at shop or factory level AFTER the strategic decision for FA has been made at the higher managerial level.

Stam and Kuula's DSS model is in essence for feasibility studies and performance analysis in the preplanning stage of (FA) implementation. Their work pointed out the need to consider the technological, economic, design, management and social impact of FMS, albeit at the operational level. The model expressed the system flexibility as a function of part complexity, production volume and batch size, and formulated the decision making process as a goal programming problem. Overall, the model did not transcend the boundaries of operations research.

Suresh proposed a DSS model for a similar problem: optimising the economic performance of FMS "in the midst of combinatorial complexities resulting from machine, expansion, routing and process flexibility". The structure of his DSS took the strategic directives for change in the manufacturing system as the given input and focused on justifying selection of physical configurations by financial and performance evaluations. Flexibility was evaluated by measures such as operational time and costs.

Mohanty described a DSS for justification of a FMS which is built at three levels: cell automation; medium-term factory planning; and long-term planning. The DSS has been applied to real cases. In all these papers, it is necessary to make implicit or explicit assumption that the upper-stream strategic decision for acquiring AMT is made, so as to simplify the effort of developing quantitative DSS tools.

2-5. On Holistic Planning Approach of AMT Acquisition

It has been widely recognized that the introduction of AMT in manufacturing means more than just the upgrading of technological capacity in the shop floor. To understand the more profound implication for the manufacturing enterprise and for its environment, the upper-stream planning and justification for AMT must therefore be integrated with the down-stream implementation and operational evaluation. Efforts have to be coordinated within every segment of the firm. Consequently, justification of AMT demands not merely a piecemeal, ad-hoc equipment replacement approach, rather, an integrated and long term planning approach.

Swamidass & Waller [1990] remarked on the fallacy of treating AMT with "pure financial justification". Since manufacturing is undergoing a paradigm shift, the financial justification criteria pertaining to the old paradigm (eg., labour-cost saving and economies-of-scale based measures) are no longer appropriate; thus the concept of justification should be revised or enlarged. As is stated earlier, research has shown a bias toward justification methods, while the two aspects of justification and planning of AMT need be treated within a single framework of competitive capability planning and implementation.

Troxler and Blank [1990] pointed out that unrealistic or incomplete considerations and planning of CIM as a productivity improvement or cost reduction alternative usually resulted in the following problems:

a) the system was implemented but the expected results were not achieved.

b) the system was not implemented and the potential for improvement was lost.

The researchers suggested that the problems should be overcome by taking a systems approach that span from preimplementation planning to post-implementation benefit tracking.

Gerwin [1982] pointed out that, besides planning for technical aspects of AMTs, planning for appropriate infrastructure should be an essential part of AMT investment. Following infrastructure areas are identified [**Gerwin**, 1982; **Goldhar & Jelinek**, 1983] as of critical importance for successful implementation of AMTs:

--Skills;

--Attitudes;

--Systems and procedures;

--Structure;

--Management commitment and policy.

Conceptual models of strategic implications of AMT investments to competitiveness are proposed by many researchers, eg., **Cook & DeVor** [1992], **Gervin & Kolodny** [1992], **Hyun & Ahn** [1992], **Sun** [1993], and **Mohanty** [1993]. While these models are valuable in that they promote a system wide perspective view of the AMT investment beyond the boundary of manufacturing shop floor, these models do not address how the actual tasks should be carried out within the conceptual framework in real situations, except for an effort made in this matter by Mohanty's model. Mohanty's model has three stages:

Stage I --Identification of potential AMS;

Stage II --Identification of various effects of AMS;

Stage III--Evaluation of effects through different decision models.

In the first stage, various steps should be pursued to identify:

--current manufacturing situations in terms of nature of business, market position, and production/operation

--future manufacturing requirements in terms of production and operations

--objectives of the organisation in terms of production & operation

--potential constraints and restrictions

--potential candidate AMT systems

The Stage II identify the effects of each potential AMT candidate.

Mohanty proposes to examine two categories of effects:

--Non-economic effects: strategic, technological, social;

--Economic effects: costs & benefits in monetary terms.

Lists of contents in each category are given [Mohanty, 1993].

In the Stage III the evaluation of effects are synthesized in order to derive measures for decision support. Development and implementation of decision support systems (DSS) were suggested to accomplish the tasks.

While closer to application than the other models mentioned above, many issues remain to be resolved. Among the important issues *measurement* and *synthesis* methodologies of the multiple factors and various effects are major areas for further research.

2-6. Literature on Technological Position Indicators

Planning for AMT acquisition deals with capacity expansion, or capability upgrading situations, with "Nonstatus quo" as the prime purposes. Alternatives for nonstatus quo objectives are usually not mutually exclusive, their selection and justification will be based on trade-off among multiple factors. A planning approach should look beyond the boundary of manufacturing for the relevant factors. A comprehensive list of attributes that influence the system value is compiled by **Troxler and Blank** [1990], who arranged the attributes into four rational groups:

a) Compliance with corporate strategy
b) Intrinsic ability
c) Physical performance
d) Financial benefits

The subattributes of each main group, and their indicators are shown in the Table 2-1.

Table 2-1. System Value Attributes [Troxler&Blank, 1990]

Strategy compliance	Intrinsic ability	Physical performance	Financial benefits
Suitability factors	Capability Factors	Performance Factors	Productivity Factors
1) Investment position 2) Growth position 3) Technological position 4) Market position 5) Employee relations 6) Workforce composition 7) Organisational structure 8) Operation management	1) Design 2) Function 3) Reliability 4) Availability 5) CIM ability 6) Flexibility 7) Human factors 8) Technological feasibility	1) Throughput 2) Quality 3) Inventory 4) Information 5) Utilisation	1) Customer responses 2) Environment influences 3) Economic infrastructur

Monhanty [1993] pointed out that there are certain overlapping or redundancy between the subattributes in this list, and proposed a somewhat different set of factors of expected effects of AMT, as shown in Table 2-2.

Table 2-2. AMS Effects [Mohanty, 1993]

Non-economic effects			Economic Effects	
Strategic factors	Technological factors	Social factors	Pre-production costs	Production costs
1) Financial position 2) Technological position 3) Market position 4) Human resource management	1) R & D 2) Mfg eng & planning 3) Flexibility 4) Compatibility 5) Reliability 6) Life 7) Data base 8) Environment factors	1) Employee policies 2) Working environment 3) Community development 4) Ecology	1) Plant & equipment 2) s/w 3) Modification 4) Engineering 5) Training 6) Any others	1) Material 2) Labour 3) Accessory 4) Quality 5) Inventory maintenance

The lists of factors are not exhaustive and the factors are to be prioritized according to firm-specific manufacturing settings. Many factors and subattributes are of a qualitative nature. Their indicators may be used as measures of factors only on subjective and relative scale, but not on absolute scale. For example, 'Technological position' has the possible indicators in following forms:

a) Modernisation	or	a) Improvement
b) Integration		b) Modernisation
c) Innovation		c) Expansion
[**Troxler&Blank**]		[**Mohanty**]

It is difficult to assign quantitative value to these indicators, but these may have direct or surrogate measures on a quantitative scale, for comparison between alternatives.

Benchmarking of manufacturing capability is required to assess the firm's "technology order", or in **Swamidass**'s term, "Monitoring technology deterioration". This task involves benchmarking of the existing technology base vis-a-vis the state-of-the-art technology in the industry, and also vis-a-vis the forecast of the technology over the planning period.

2-7. On evaluation and synthesis of impacts on factors

The multiple factors included in the AMT strategic planning raise serious questions with regard to evaluation and synthesis of their impacts on AMT investment. In analyzing the data requirements for manufacturing strategy planning, **Primrose & Verter** [1994] point out that, because of the very large amount and inexact nature of the data, "the type of analytical methodology that has been developed in the past is far from being able to incorporate all the relevant factors in practical applications. Although operations research techniques have also been used to develop methodologies for other aspects of manufacturing strategy, such as capacity acquisition and technology selection, these also are incapable of considering the large amount of relevant data in practical applications".

In addition to the amount and nature of the data, cross-impacts of factors inevitably result in certain conflict in objectives, therefore the evaluation and selection of the alternatives necessarily require ranking, weighing and trading-off among the factors and attributes [**Sullivan**, 1986; **Canada**, 1986]. In these type of multiple criteria decision making (**MCDM**) problems, the objective is described by the MCDM theory as conflict resolution, or more often, the conflict-reduction [**Zeleny**, 1982].

The MCDM process having large amount of qualitative data may be handled with the analytic hierarchy process (**AHP**) methodology developed by **Saaty** [1980, 1982]. There have been several accounts of applications of AHP to the justification of certain types of AMT: **Boucher & MacStravic** [1991] tried to relate the AHP with the present worth (NPW) approach of AMT justification. **Weber** [1993] modified the classical weighting scheme of AHP by incorporating original quantitative values of the quantitative factors in the pairwise comparison. **Liberatore et al** [1993] built the hierarchy with layers representing corporate mission, objectives, and strategies for capital budgeting purpose. **Mohanty** [1993] applied AHP in the cost/benefit analysis for selecting AMS. **Basu et al** [1994] applied AHP to a problem of selecting among Group Technology alternatives. **Leung & Azhar** [1993] proposed an application of the more general form of AHP, the System-with-Feedback methods [**Saaty**, 1980], to the capital equipment replacement decisions. In this model the interactions of the criteria and subattributes are taken into account. This is the relaxation of one of AHP method's basic assumption of independence of criteria, hence a step closer to the reality.

In these efforts, the factors or criteria considered vary from researcher to researcher, the scope of problems differ as well. These reflect the situation specific nature of the AMT acquisition problems, as well as demonstrating the adaptabiliy of the AHP method.

Most attempts in the literature on applying AHP to the AMT acquisition problems have exploited the forward AHP process for selection and justification. The iterative function of AHP for planning has been less vigorously explored. An integrated planning approach for AMT implementation may enable a better exploration of the advantages of the AHP in this aspect.

2-8. Summary and Further Definition of the Research Objectives

Review of the literature reveals that there are attempts to address various aspects of AMT investment planning and justification problems, which involve multiple factors of qualitative and inexact values. The previous endeavour can be grouped into two broad categories: planning and justification [**Swamidass&Waller**, 1990]. What seems lacking in the existing literature is the integrated methodology for AMT investment planning and justification, which is what industry is really interested in. Further, the existing researches on AMT adoption focus mainly on selecting AMT alternatives on basis of technology aspects, with insufficient attention to implementation requirements and infrastructural impacts.

The objectives (see §1-2.) of this thesis are specified as:

1) To develop an operational procedure of a '*Backcasting*' framework of AMT planning and justification, on the foundation of manufacturing capability building concept, which i) adapts activity based performance measures into capability positioning indicators; ii) incorporates implementation consideration into AMT investment planning and justification; and, iii) is applicable in industrial settings as a decision aid. The structure and functioning of the backcasting framework are described in detail in the following chapters.

Chapter 3.

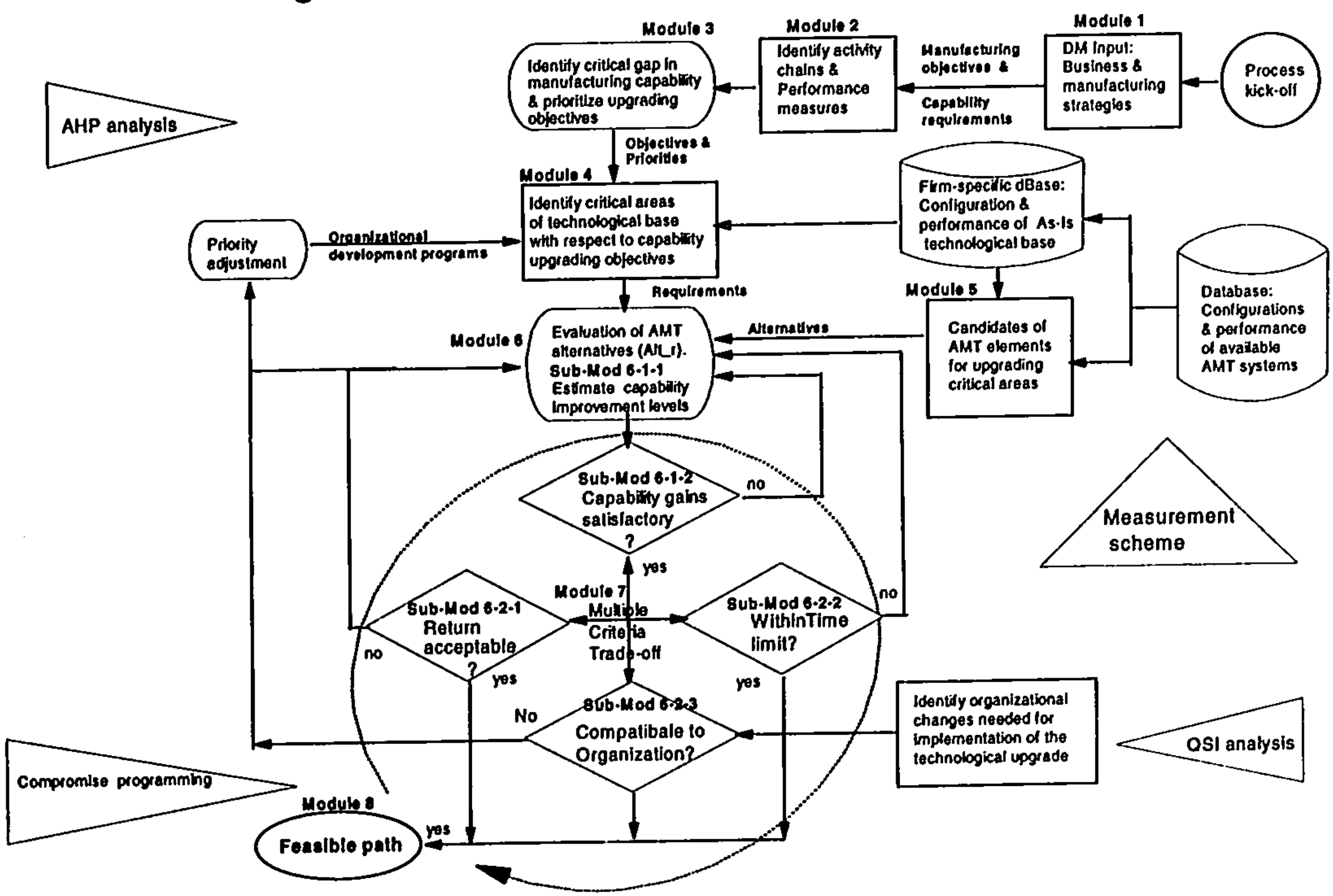
Outline of the Proposed Framework

To address the problems identified in the previous chapters, a framework of AMT planning and justification is presented here. The framework takes a backcast approach, in which the AMT acquisition is modelled as an essential effort in a process of building key manufacturing capabilities for a firm's long term competitive positioning. Intangible benefits associated with AMT acquisition are explicitly considered and modelled as a set of manufacturing capability measures. Backcasting of AMT acquisition works its way from defining strategic capability objectives, through identifying the capability upgrading needs or gaps, to determining the most appropriate upgrading program alternatives to close the gaps. The flow diagram of the conceptual framework is shown in the Fig.3-1. The modules in the diagram are briefly described in the Section 3-1 below. The in/output are elaborated in more detail in the remaining sections of this chapter.

3-1. Description of the modules in the conceptual framework

Module 1. *Define environment, bench marks and requirements:* Corporate strategic guidelines and industry bench marks are taken as input to set manufacturing capability requirements for the planning horizon.

Fig.3-1. Flow diagram of the backcast framework



Module 2. Analyze activity chains and establish performance measures:
Major activities in a firm's manufacturing process are identified and analyzed. Activity-based performance measures are established accordingly.

Module 3. Identify performance capability measures and gaps:
Strategic capability requirements are decomposed into operational performance targets with quantitative measurements; Capability gaps in each measure are assessed.

Module 4. Identify critical technological areas:
Criticality of each area in technological base is assessed with respect to closing the capability gaps found in Step 2; priority of upgrading needs identified.

Module 5. Identify technological upgrading alternatives:
Available technological sources are scanned and possible upgrading program alternatives identified.

Module 6. Evaluate upgrading program alternatives:
Expected levels of improvements towards the targets in each category of performance measures are estimated for every alternatives.

Sub-Module 6-1. Estimate performance levels and Calculate capability improvement rates:

Degree of capability improvement due to each alternative in one category of the performance measures is computed as percent closure of the gap. Composite improvement rates are then computed as the weighted sum of the percentage degrees over all categories of performance measures.

Sub-Module 6-2. Evaluate implications of technological programs to other factors:

Quantify and calculate the implications of the alternatives to other influencing factors, which may include, eg.:

Sub-Task 6-2-1. Money: estimate ROIs of each Alternative;

Sub-Task 6-2-2. Time: compare time needed for project implementation;

Sub-Task 6-2-3. Organization: estimate possible organizational adjustments needed for each alternative.

Module 7. Establish decision criteria, & Select the most appropriate alternative by Compromise Programming method:

Quantified evaluation scores of each alternative, obtained from previous modules, (Module 6 in particular), are synthesized into composite decision indices and compared to identify the most appropriate program under the given conditions.

Module 8. Recommendations of THE technological program: Elaborate the trade-offs between the multi-criteria of Module 6, and make a presentation of the recommended technological upgrading program.

Module 9. Identify organizational development programs: Output of Sub-Task 6-2-3 may be used as the input for further designing organizational development programs as would be required by the integrated capability building efforts.

3-2. Input to Module 1: Summary of Strategic Planning Process

The Step 1 of the framework in Fig.3-1 takes business and manufacturing strategies as input. It is not the purpose of this thesis to develop business and manufacturing strategies. A brief citation of the well documented strategic planning process will suffice here.

Strategy can be defined as a general approach that an entity will take in order to achieve its long term goals. Strategies are hierarchical, corresponding with the structural hierarchy of its owner. Typical large, multi-divisional business firms have three levels of strategy: 1) corporate, 2) business, 3) functional. [**Oden,** 1992].

Corporate strategy determine business niches in which the firm decides to compete, and the relative emphasis that will be placed on each business in the portfolio.

Business strategy associate with divisional level and emphasize the improvement of competitive position of a corporation's product / services in the specific industry served by the division.

Functional strategy describe how functional departments will utilize resources and coordinate actions to maximize the performance in support of the implementation of higher level strategies.

For typical small-medium-sized manufacturing firms, one may expect less clear distinction between levels or types of strategies. It is assumed that these firms are guided by a combined manufacturing strategy, which merges corporate and business strategies.

The strategic management process involves three major activities:
1) Strategy formulation, 2) Strategy implementation, and
3) Assessment. [**Oden,** 1992]

The activities can be decomposed into 5 tasks:
1) Objective setting - determine the direction and goals for

the firm and its business units;

2) Strategic programming - develop strategy and define cross-functional programs;

3) Strategic and operational budgeting - strategic budgeting specify the contribution from each business units toward the corporate goals, and operational budgeting determine resource allocation;

4) Monitoring, control and learning - emphasis on meeting the key milestones and schedules of implementation;

5) Incentives and staffing - critical steps in implementation. [**Chakravarthy & Lorange,** 1991]

3-3. Generic Manufacturing Strategic Goals-Output of Module 1

The types of manufacturing strategies that emerge from the above process are necessarily firm-dependent. Nevertheless, certain generic manufacturing strategic goals have been documented in literature. Company-specific goals can be assumed to be a variant set of the generic goals with firm-specific weight assigned to particular goals.

Manufacturing strategic goals are suggested as including the following [**Maskell,**1991; **Ferdows & Meyer,** 1986]:

--Low cost manufacturing

--Quality

--Productivity

--Flexibility

--Service

--Dependability

--Lead Time

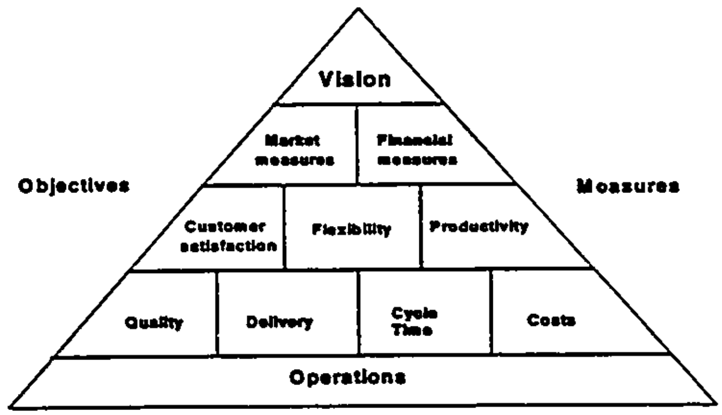
--Delivery Reliability

--Employee Relationships

Overlapping exists among the goals. For example, productivity, service, dependability and time represent similar concerns as to that of cost, quality and delivery, respectively. Fig. 3-2 is a pyramid of objectives, from Wang Corp. [**Maskell**,1991]. Setting and prioritizing of the goals is a firm-dependent exercise. The proposed framework offers the flexibility for decision makers to determine any set of manufacturing strategic goals as the starting point. For illustration purpose of this thesis, it suffices here to base the further discussion on a selected set of the goals: Cost, Quality, Flexibility and Delivery. The four goals are essential for any manufacturing firm to survive and succeed in the market place. An elaboration of the four strategic goals is given below:

1) Costs -- To manufacture at the lowest possible costs in order to support the business goals of earning and market share. Relevant costs in the new paradigm are activity-based and include value-adding costs, wastes costs and quality costs, as opposed to the labour costs orientation in the old paradigm.

Fig.3-2 Objectives and Performances Pyramid by Wang Laboratories Corp.



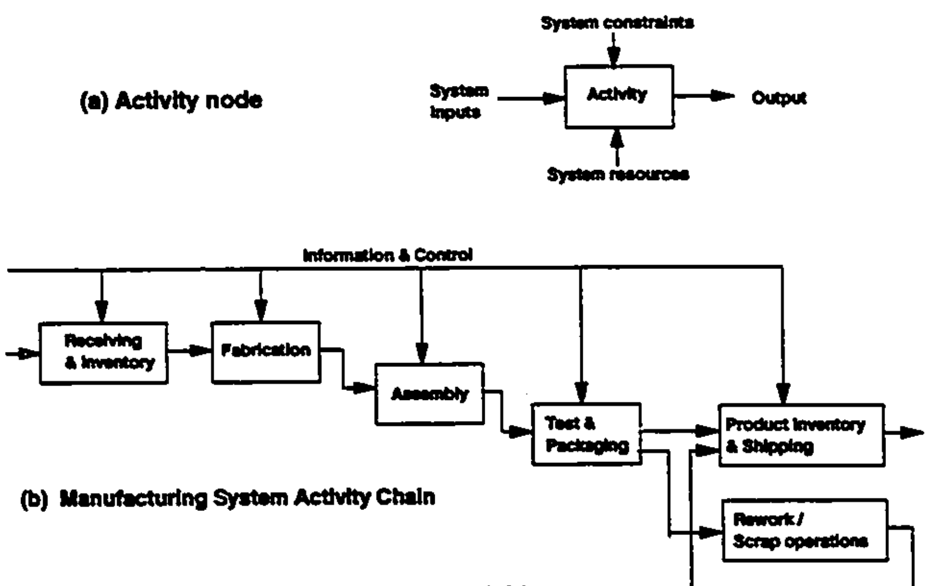


Fig.3-3 IDEF. Representation of Activities

2) Quality -- concerning three aspects:

a) Quality of design -- conformance of product and process design to functional, economic and environmental requirements;

b) Consistent high production quality -- conformance to product specifications, eg., Zero Defects, Process capability for tight specification limits;

c) High performance quality -- embracing both performance quality, reliability and durability.

3) Flexibility -- multidimensional, major ones may include:

a) Product mix flexibility -- the ability to accommodate changing product designs for customization or variety;

b) Volume flexibility -- the ability to quickly accelerate or decelerate production rate to handle fluctuations in demand;

c) Changeover flexibility -- the robustness of the system to withstand product discontinuity with minimum disturbance and costs.

4) Delivery -- the time-related goal, consists of three dimensions:

a) New product introduction -- shorter time from design to market;

b) On-time delivery of existing product -- the ability to meet delivery time promises;

c) Fast delivery -- shorter customer order cycle time.

Delivery (time-based) objective is particularly emphasized by many researchers and practitioners as the characteristics of new competitiveness. [**Stalker,** 1993; **Sonnenberg,** 1993]. Prioritization of objectives, and performance measures associated with these objectives are given in later sections.

3-4. Manufacturing Capabilities for Achieving Strategic Goals -- Parameter definitions and measurements

Once the strategic manufacturing goals are set and prioritized, the firm needs to assess its existing capabilities for achieving the goals, and set out to build or enhance the key set of capabilities if any deficiency are found. Manufacturing capabilities are inherent attributes of manufacturing firms' overall ability to stay in business and compete for success. While operating objectives may be set within the constraint of existing capabilities, strategic goals, or 'strategic intents', should be set in such a way as to stretch the manufacturer, hence dictating the type and level of new capabilities the firm needs to build for future success [**Hamel & Prahalad,** 1989]. Since manufacturing capabilities are dictated by manufacturing goals, the capabilities can be measured by the performance levels that a firm is able to achieve toward the set manufacturing goals.

Three requirements are critical for performance measurements associated with AMT:

a) Measures must be relevant in the new paradigm, that is, non-financial measures should be used whenever possible.

b) They must lead to right direction for improvement actions.

c) They must be simple to apply and easy to understand.

Various possible measures for assessing manufacturing performance vis-a-vis the categories of major manufacturing objectives can be found from literature. Of which the most comprehensive are the works by **Maskell** [1991] and **Oden** [1992]. The Table 3-1 below summarizes the relevant measurements by categories.

Table 3-1. Manufacturing Objectives and Performance Measures

Strategic Objectives	Manufacturing Objectives	Performance Measures (Maskell)	Performance Measures (Oden)	Measures by others
Low Cost	Min Labour costs	DLP=(Value of products completed per period) /(# of DL). Value-adding cost per unit=(Total DL+OH) / (Total Prodn)	DL/unit; InL/unit	RWSC [Son,1991; Stam&Kuula,1991] N/A [Montgomery &Johnson, 1974]
	Min Waste	Non-value-adding activity costs	N/A	
	Min Inventory	Inventory turnover & WIP turnover	Inventory& WIP	
Quality	Min production Non-conformance	# of production failures; Failure costs	No. of failures & failure costs	Quality costs [Dale&Plunkett, 1991; Son,1991]
	Max Design & planning conformance	Data quality; schedule accuracy	N/A	Concurrency costs
Flexibility (i) Product	Max pdt modification ability (customisation)	Parts commonality; Process commonality	ECO processing time	RISC [Son,1991]; Sensitivity costs [Chryssolouris &Lee, 1992]; [Gerwine &Kolodney, 1992]
	Max ability to make variety of pdt in a short time	# of different process in plant; Commonality of process across the product lines; Position of variation;	Setup time; Scheduling speed; MLT; BOM level	
	Max ability to introduce new pdt	Number of new products introduced per period	Time - prototyping to market*	
(ii) Changeover	Max process robustness in product discontinuity	n/a	Time - retooling & programming; Time - retraining; Changeover costs	
(iii) Volume	Max volume flexibility	Cycle time; Setup time	Throughput time; Setup costs	Cost Leverage [Azzone& Bertele, 1989]
Delivery (i) New product	Min new pdt introduction time	n/a	Time - prototyping to market	New product rate; New product interval
(ii) Existing product	Max On-time delivery	Service level; P:D lead time ratio; Cycle time	Marginal cost of rerouting; Scheduling accuracy; % On-time delivery	Service level(%); Cycle time; MLT; [various authors]
	Fast delivery (Min MLT)	Cycle time; Setup time	Order entry time; Setup time; % Waiting time in MLT	

(In Column 2: Min → minimize; Max → maximize; pdt → product; MLT = manufacturing lead time)

The broad strategic objectives are translated into more specific manufacturing objectives and are further broken down into performance measures relating to the different aspects of the manufacturing operations. It can be seen from Table 3-1 that some measures are used for more than one category, due to the hierarchical relationships between the objectives described earlier. Also note that the measures of performances suggested by others (the last column in Table 3-1) mainly use financial (costs) measures as opposed to physical measures. As mentioned earlier, financial measures are used for external reporting but are less useful for internal capability assessment, because these measures do not lead to identification of capability gaps in the technological base. [Maskell, 1991]. The measures by Maskell and Oden are adapted as the basic manufacturing capability indicators for the present research.

These Objective-Performance measures are extended in Table 3-2 to establish correspondence between the core manufacturing objectives, manufacturing performance measures, functional activities that identify with the performance categories, and the factors upon which the capabilities to execute the activities are built.

Table 3-2. Manufacturing Objectives, Performances and Driving Factors

Manufacturing Objectives	Performance Measures	Functional activities driving the performances	Factors that limit the performance capability
Max Manufacturing Productivity	Value-adding cost per unit	Process planning;	Technological base; Organizational base & other factors
		Process monitoring control	
Min Waste	Non-value-adding activity costs per unit	Process design;	
		Planning;	
		Scheduling	
		Process monitoring & control	
		Communication	
Min production non-conformance	Defects rate; Process capability ratio	Concurrent design;	Technological base; Organizational base & Other factors
		Maintenance planning;	
		Process monitoring & control	
Max Design & planning quality	BOM accuracy; Routing accuracy; Process planning accuracy	Data base maintenance	
		Data collection & processing	
		Concurrent design	
Max product modification ability	Parts commonality; Process commonality; ECO processing time	Database maintenance & access	Technological base; Organizational base & Other factors
		Design-Planning communication	
		Design-manufg communication	
Max ability to make variety of pdt in short time	# of different process in plant; Commonality of process across the product lines; Position of variation; BOM levels; Scheduling speed; Setup time; Cycle time	Design database	
		Planning	
		Scheduling	
		Concurrency	
		Data handling	

Table 3-2. Manufacturing Objectives, Performances and Driving Factors

Manufacturing Objectives	Performance Measures	Functional activities driving the performances	Factors that limit the performance capability
Max On-time delivery	Service level; P:D lead time ratio; Cycle time; Scheduling accuracy	Process availability Concurrency Process control Data handling	Technological base; Organizational base & Other factors
Fast delivery (Min MLT)	Cycle time; Setup time; Waiting time; Order entry time	Concurrency Process control Data handling	

Table 3-2 is organized in a hierarchical structure from left to right. The columns 1 and 2, representing the manufacturing objectives and measures, are extracted from the table 3-1. Columns 3 and 4 are constructed based on the following propositions:

a) The value-chain of manufacturing systems can be divided into functional activities;

b) The performances in the column 2 are determined by the effectiveness and efficiency of executing the activities identified in column 3;

c) Capabilities for executing the tasks of the column 3 are built from interactions of the following factors: Technological base, Organizational base and other factors (company resources in terms of capital and time, eg.), listed in the column 4.

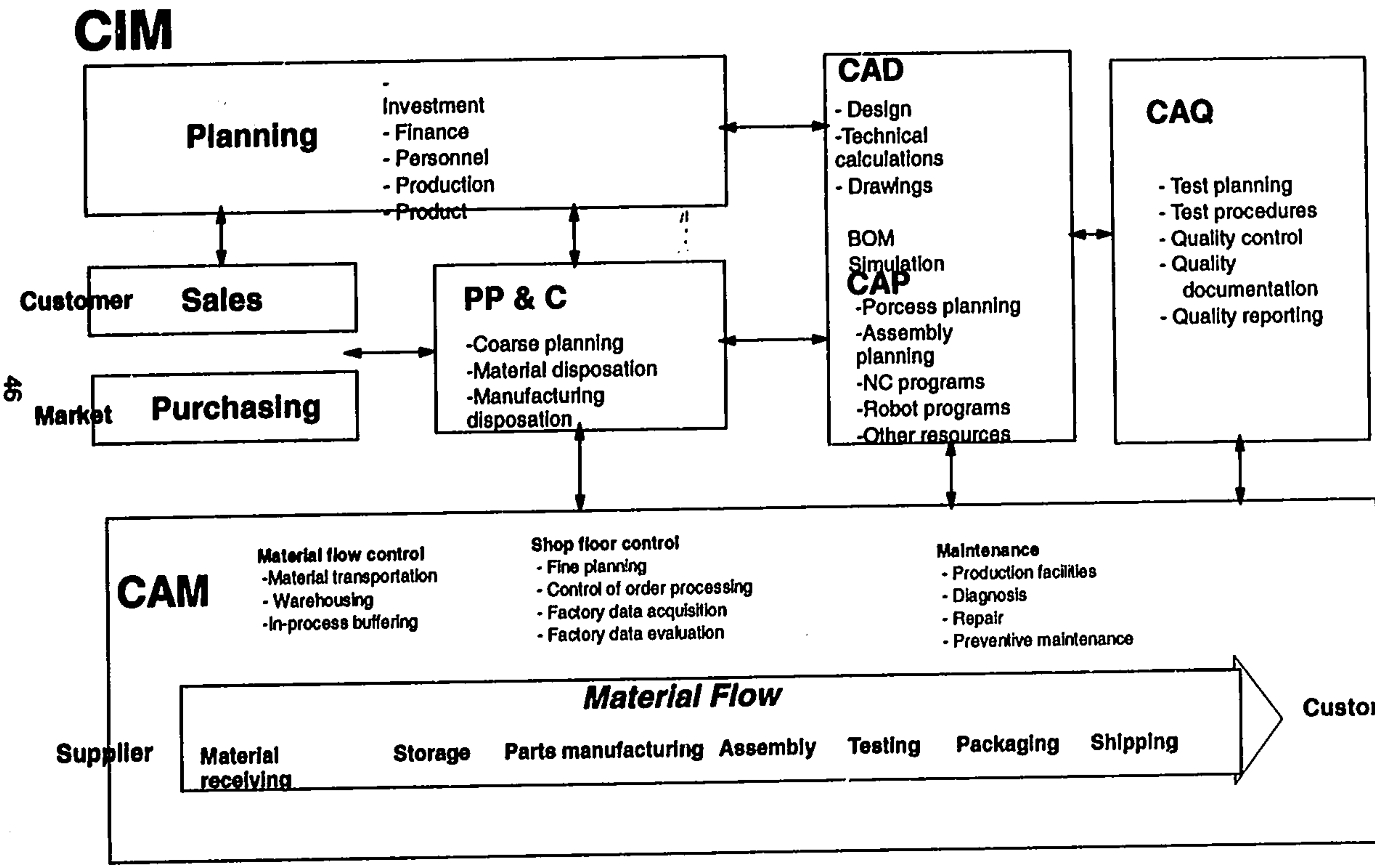


Fig. 3-4 Functional Components of CIM Environment by Siemens

The row 1 and 2 correspond to the Low Costs Goal (Table 3-1). The relevant cost items should be activity-based. Inventory & WIP measures (Table 3-1) are excluded because the levels of inventory and WIP are dependent on the cycle time and delivery which are evaluated as independent variables.

Identification of the functional activities that drive the performances (column 3) is one critical link between setting the activity-based performance objectives and the capability influencing factors (Columns 2 & 4). Elements that are to be included in the column 3 need be firm-or-situation-specific. Nevertheless, general models of value-chain concept can be used to provide guidance to the task. Fig.3-3 is a model of activity decomposition, based on the *Integrated Computer-Aided Manufacturing Definition (IDEF)* approach developed by the US Air Force [**Mitchell,** 1991, p20-23]. In this model, manufacturing systems are represented as a chain of activities, each of which takes an input and produces certain outputs under system constraints. The system resources, not shown in Fig.3-3, may comprise technology base and skills.

Fig.3-4 shows the functional activities in a CIM environment. [**Rembold et al.** 1993, p54]. The model, developed by Siemens AG, Germany, emphasizes the integration of information and material flows through a manufacturing organization. Facing the diversity of manufacturing practice, one can adapt the basic approach of Fig.3-3 and 3-4 to situation-specific analyses for identifying activity chains, as will be shown in the case study in a later chapter.

The factors in the column 4 of Table 3-2 are identified on the following bases: Recalling the definition of technology [**Noori& Radford,** 1990] quoted in the chapter 1, these factors form the hardware, software and brainware of the technology base, as well as the supporting network. Interactions between these factors are the subject of active research. A "MOST" model [**Sun,** 1993] is shown in Fig.3-5 as a simplified representation of the interactions of the key factors. The model helps to illustrate the dimensions of the manufacturing capability building efforts, when a holistic view is taken. For the purpose of this thesis, Technological base is the focal point. And the functions of design, planning, and manufacturing control activities are main concerns for capability building.

Attributing the levels of performance of particular objectives to the relevant functional activities (column 3), and in turn to the factors (column 4) is a task of subjective judgement, and is also firm-specific. Subjective evaluation and rating methods will be discussed in the next chapter. It suffices here to state that the hierarchical structuring of the problem lends itself to the analytic hierarchy process (AHP) method.

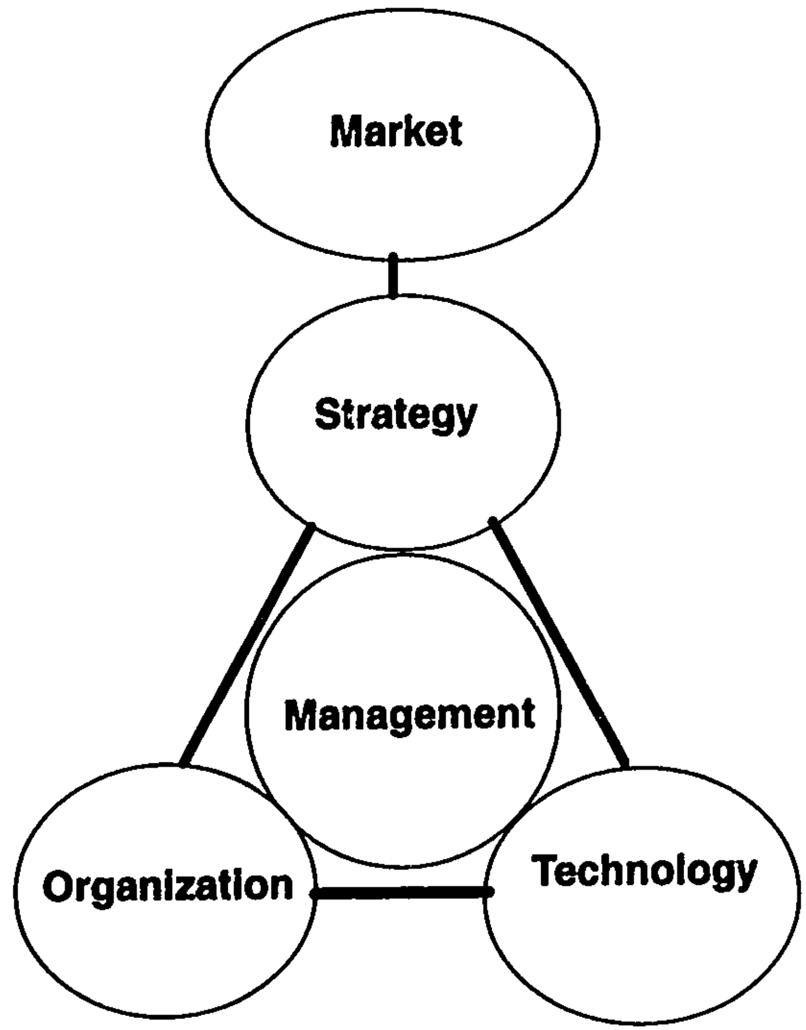


Fig. 3-5 The MOST Model: Market-Organization-Strategy-Technology

3-5. Determine Capability Targets and Gaps for Improvement

Table 3-2 establishes the linkage between achievement of strategic manufacturing objectives and certain core manufacturing capabilities. For example, the capability to minimize the quality nonconformance serves both high quality and low costs goals. Likewise, capabilities that are essential for achieving product mix flexibility are also essential for achieving time-related goals (delivery). This is to be expected since the strategic goals are interdependent rather than exclusive of one another.

Prioritization of manufacturing objectives for a specific time horizon is a firm-specific management decision. *Target* levels of manufacturing capability build-up required for serving the objectives can in turn be established, using the same set of capability indicators (ie, the performance measures) as suggested in the Table 3-1 and 3-2. References to industrial bench marks and current system configurations have to be made. The differences between the current levels and the desired levels of particular capability aspects define the firm's manufacturing *Capability Gap* that must be closed so as to achieve its strategic goals. For example, suppose quality and product variety are the major goals and the manufacturing objectives are set to achieve: a) for quality conformance capability, a reduction in the number of defects from current level of 100 ppm to 10 ppm, and b) for fast delivery, a reduction in manufacturing cycle time from 50 hours to 20 hours per batch in average. The gaps in each case are 90 ppm and 30 hours, respectively.

3-6. Develop capability upgrading program alternatives

Identification of capability gaps is followed by development of *Capability Building Programs*. The programs refer to the possible plans for AMT acquisition, with reference to the information of available AMT options from various sources. Organisational development and training are most likely to be required as integral part of the programs over the planning period, due to interdependence between the influencing factors of organisation and technology. Therefore, the capability building programs boil down to the phased development in high priority areas of technological and organisational bases. In other words, while the gap identification answers the question *Why*, the programs provide *What* and *How*.

3-7. Summary of the Chapter

The 'backcast' capability upgrading framework is outlined, with a description of its major modulus component blocks. The number of dimensions and parameters identified in the discussion suggests the level of complexity of the task. Multi-factor interaction analysis and synthesis methods will be the subject of the next chapter.

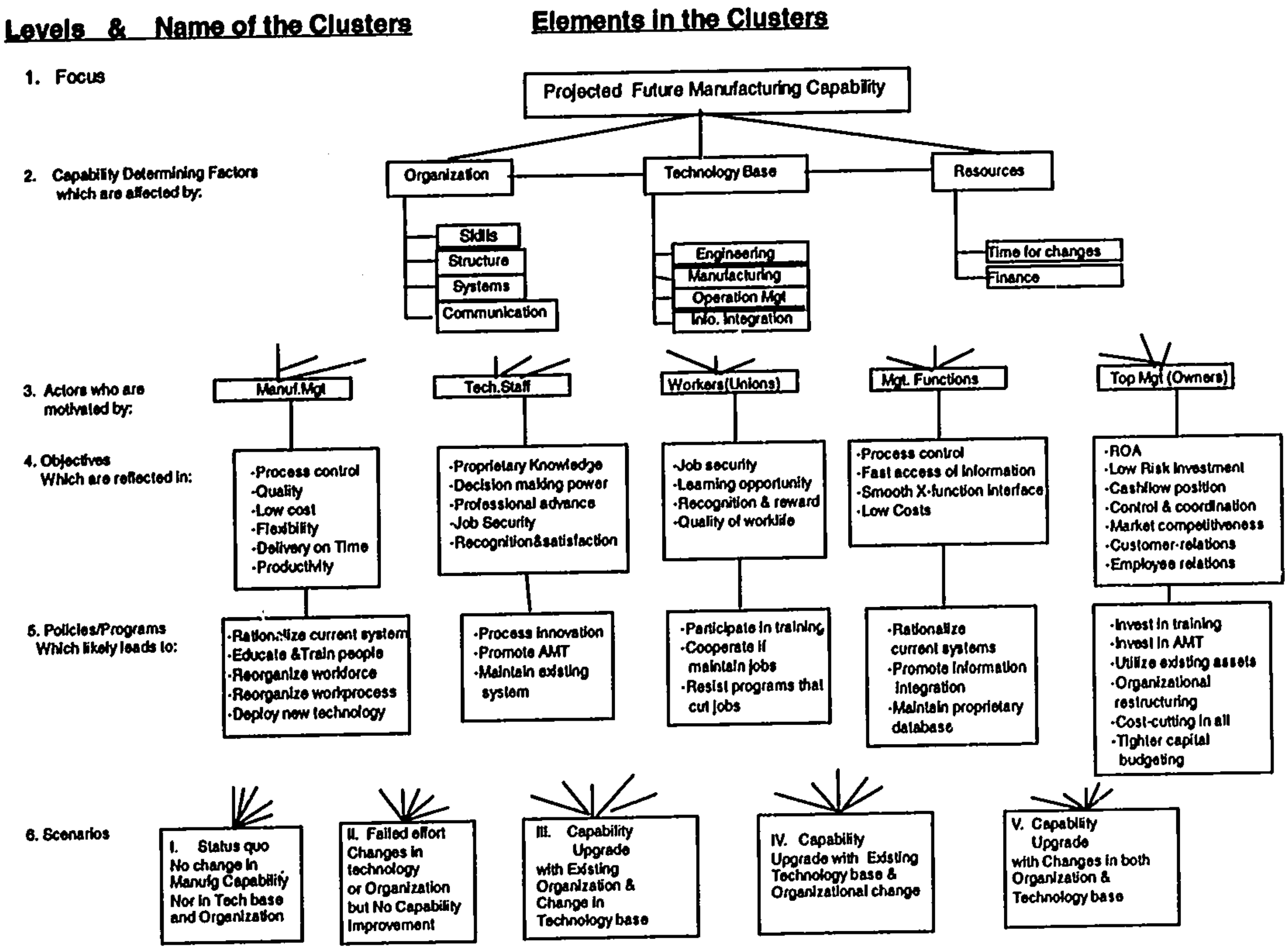


Fig.4-1 Forward Planning Hierarchy

Chapter 4.
Influencing Factors and Interaction Assessment

The capability upgrading process spans the entire range from goal setting, problem area identification, alternative development and assessment analysis, as outlined in the previous chapter, to the synthesis and selection of the improvement program. A range of factors affect the fulfilment of the tasks and the outcomes of the process. Figure 4-1 shows a holistic view of the key influencing factors for this process in a hierarchical structure, and the likely outcomes of the improvement efforts. It is modeled as a Forward Planning Hierarchy [Saaty, 1980]. The complete AHP analysis on a problem of such a scale and depth is, however, beyond the scope of this thesis. The focus here is on the upper level factors, which are briefly mentioned in the Tables 3-1 and 3-2 in the previous chapter, and defined in more detail below.

4-1. Assumptions about factors that affect the achievement of manufacturing objectives and their assessment

1) Goal setting and order of priority of manufacturing objectives are inputs by management under firm-specific conditions for a given time horizon, as stated in Chapter 3.

2) Capabilities to achieve the objectives are dependent on

three groups of factors internal to a manufacturing firm:

--Technological base (existing base, and development potential)

--Organizational base (existing base, and possible path of change)

--Resources available to the organisation (current and accessible, referring mainly to capital, skill, and time)

These factors form the second level of the hierarchy in Fig.4-1. Interdependence of the Objectives (Level 1) on the Factors (Level 2) are represented in Fig.4-2. (Also see Table 3-2)

3) Each factor in the clusters in Fig.4-2 consists of a sub-hierarchy, the elements are depicted in Fig. 4-3 (Technological base), Fig.4-4 (Organisational Factors), and Fig.4-5 (Resource Factors).

4) The impact on the Capability objectives by Organizational, Technological, and Resources factors, indicated as directed arcs in Fig.4-2, can be weighted by their *Impact Priority* with respect to achieving the capability objectives.

5) The functioning of influencing factors in Fig.4-2 are further affected by a number of forces (actors within the firm). The major ones form the Level 3 elements in the hierarchy of Fig. 4-1.

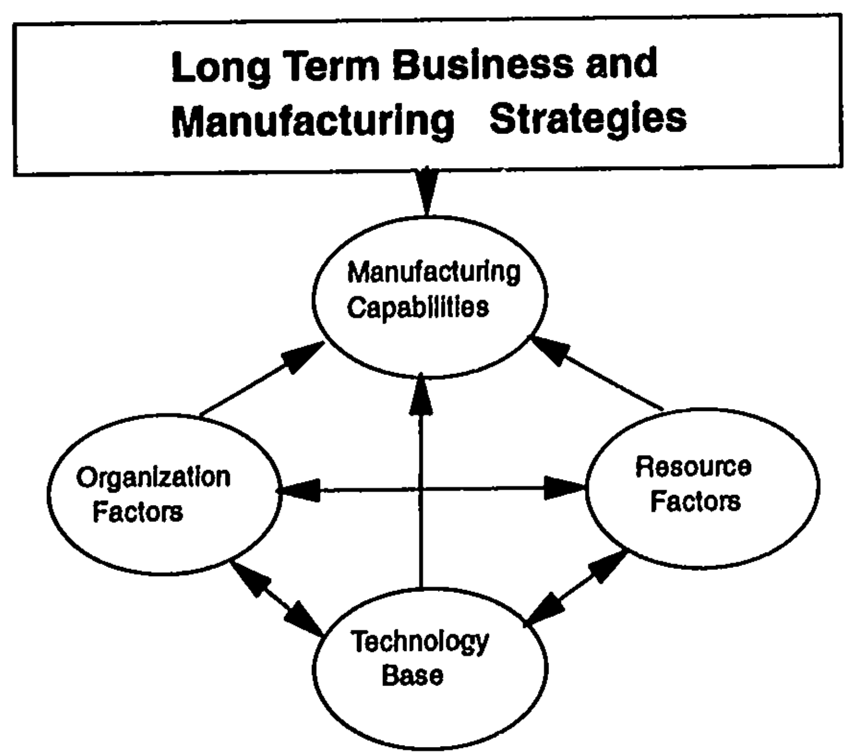


Fig.4-2 Performance Capabilities and Determining Factors

6) The *Relative Impact Priority* of the clusters, and sub-attributes within the clusters, can be obtained by pairwise comparison of the cluster components with respect to other clusters or sub-components upon which they have an impact.

7) The *Eigen vector method*, developed by **Saaty** [1980,1982], shall be applied to the pairwise comparison outcomes to calculate the quantitative value of the *Impact Priorities*.

8) Where quantitative (physical measure) values of attributes are obtainable, these values should be used in determining the relative weights of the pairs of subcomponents being compared [Weber, 1991].

9) Where no relevant quantitative (physical) values are available for the pair of subcomponent attributes being compared with respect to certain criteria, classic AHP subjective weighting scale of 1 - 9 [**Saaty**, 1980, 1982]) will be used to determine the relative weight.

10) The merge of the subjective weighting (classical AHP method, see **Saaty** [1980]) and objective measures (modified AHP method, see **Weber** [1993]) in one hierarchical analysis will yield valid measures of Impact Priority at least as good as the all- subjective weighting method.

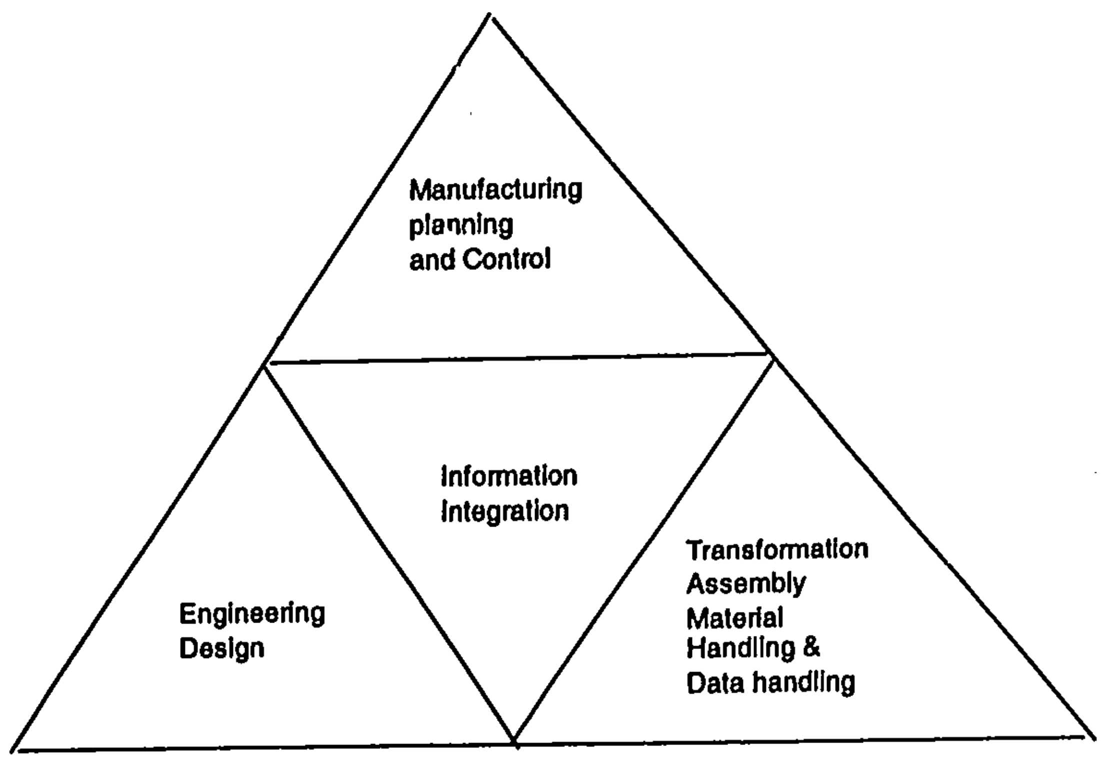


Fig.4-3 (a) Categories of Technological Factors

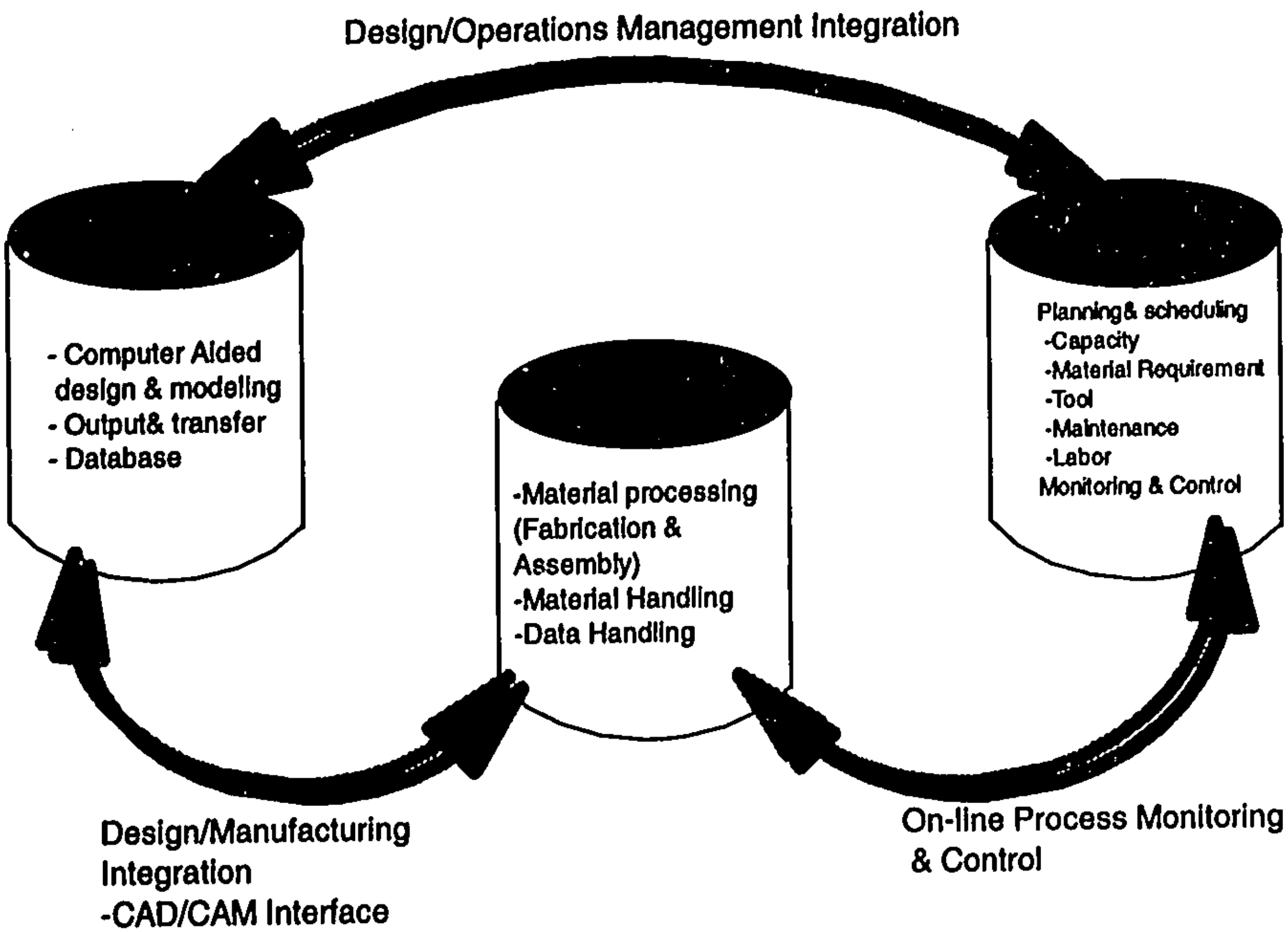


Fig.4-3 (b) AMT Components & Elements by Activity Areas within Manufacturing

4-2. Discussion on the Components of Influencing Factors

I) Sub-categories and elements in the Technological Factor

There may be different ways of classifying the components of the technological base, representing different level of details. For the purpose of this discussion the approach of functional modelling is adopted, in which the technological base comprises four categories indexed k=1,2,3,4 and each consists of subcomponents p=1,2,3..p(k), as in Table 4.1:

Table 4.1a

	Design & Engineering Automation: k=1	
Sub areas	p=1	p=2
	Design & Analysis tools	CAD/CAM I/O, Database & Transfer tools
Functional objectives	Product & process design, Functional analysis to generate drawings, BOM, BOR, & NC programs	Input & Output drawings, product documents, BOM, & NC programs, Store & Transfer to other business functions
Embodiment Elements	CAD/CAM systems Interactive Graphics, NC-Programming s/w Simulation s/w, Synthesis & analysis system, H/W platforms	Blueprints, Tapes & disks, Scanners & Plotters Electronic database & data transfer means

Table 4.1b

	Manufacturing Shop floor Automation:k=2		
Sub areas	p=1	p=2	p=3
	Material Processing	Material Handling	On-site Data handling
Functional objectives	Automatically Fabricate Transform & Assemble products	Automatic physical flow integration	In-process data capture & transmit
Embodiment Elements	Machining stations & modules, Robots, Tool changers	AGVs, Robots, Conveyors, AS/RS	Sensors Scanners Gauges, CMM

Table 4.1c	Manufacturing Management Systems: k=3	
Sub areas	p=1	p=2
	Production Planning & Scheduling tools	Shop floor Monitoring & Control Tools
Functional objectives	Generate order specific process plans & real time schedules	On-line monitoring & control of production process, Automatic download of control message to M/C, & Data upload to controller
Embodiment Elements	CAPP systems, MPS tools, MRP & MRP-II s/w	CAQ system, Tool status, Time, WIP & inventory tracking & control systems

Table 4.1d	Information Integration (Networking): k=4	
Sub areas	p=1	p=2
	Design-Manufacturing-Management Integration (k=1)∩(k=2)∩(k=3)	Enterprise integration
Functional objectives	Concurrent design of product & process, Order Entry & planning, Order release control, ECO processing & costing	Communication cross Manufacturing & other functions internal / external to the firm
Embodiment Elements	GT-oriented database & data distribution, Process capability feedback network and interfaces, LAN	MIS, LAN & WAN, Interfaces

Detailed descriptions of some of the elements can be found in **Mitchell** [1991], and **Stark** [1989]. The emphasis for areas k=1,2,3 is in the automation and local loop of information flows within each area, while the information flow and integration between the areas is the emphasis of k=4. This division corresponds to the two dimensions of technological areas: automation and integration.

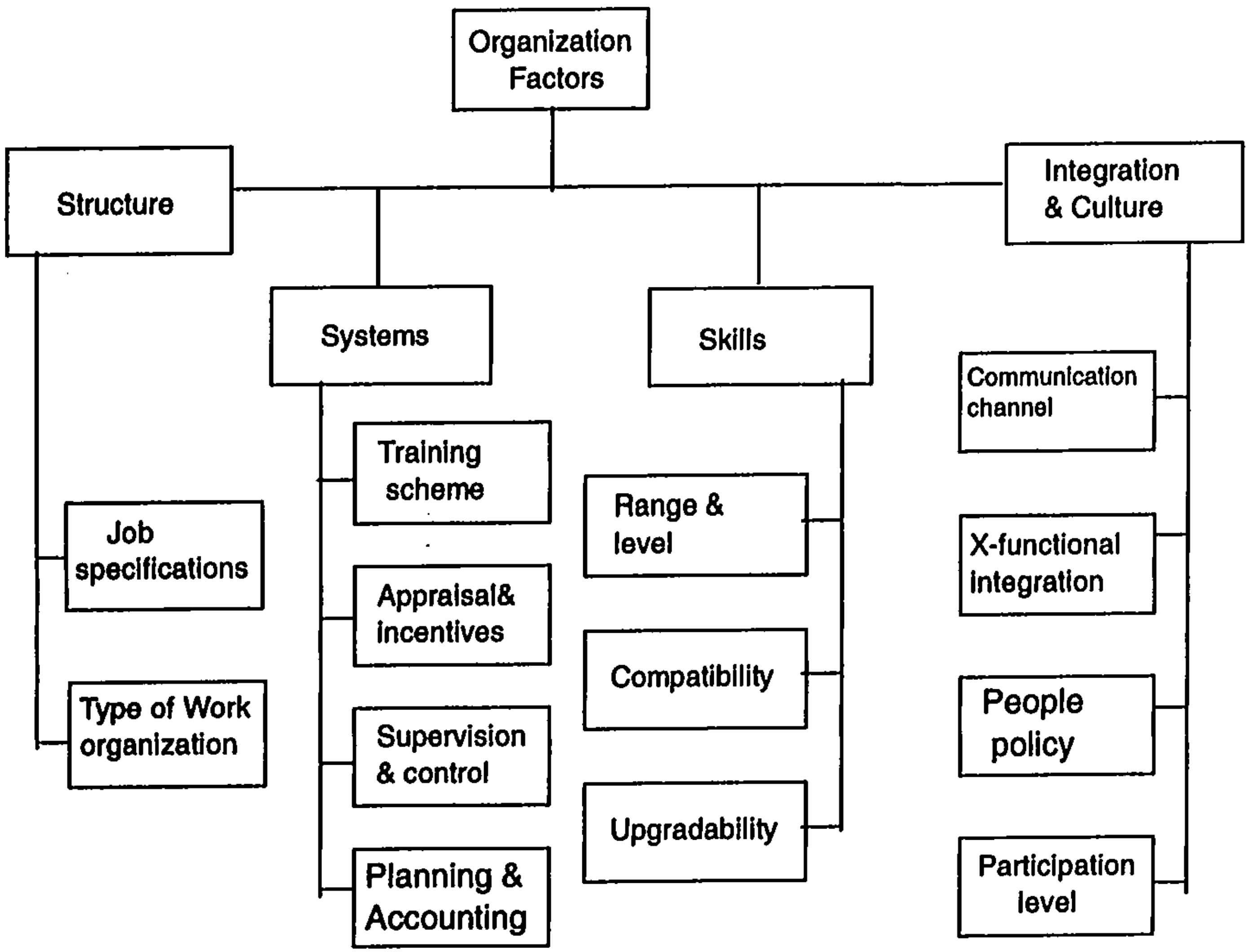


Fig.4-4 Organizational Factor Components

II) Sub-categories and Elements in the Organisational Factor

Organizational issues relating to advanced manufacturing technology implementation are examined with respect to various dimensions. The researches in literature have covered the aspects as in Table 4.2 below:

Table 4.2. Organizational Dimensions Identified by Researchers

Researchers	Organizational dimensions of recent research
Ettlie [1987,88]	Participation; Training; Human resources policy.
Bessant [1988,90,92]	Skills; Functional integration; Vertical integration; Work organization; Inter-firm integration; Cultural integration.
Voss [1988, 1991]	Involving the work force; Acquiring appropriate skills; Organization changes.
Mitchell [1991]	Human resources and skills; Management systems; Information flow pattern.

The researches listed above address organizational issues in wider perspectives rather than focusing on manufacturing firms alone. Changes are expected in all aspects in manufacturing organizations both as conditions and as consequences of AMT implementation. [see, eg., "Factory of the future", in **Noori & Radford**, 1990]. Nonetheless, as a simplifying assumption in this thesis, technological capability building is pivoted around four organizational aspects as shown in Fig.4-4, and in Table 4.3:

Table 4.3 Dimensions and Components of Organizational Factor

Dimensions	Components and Ranges of Elements	
Structure	Type of work organization	functional line structure to matrix type project teams; number of levels in the hierarchy; sizes of work groups.
	Job content of workforce	single task to multi-tasks roles; operating to supervisory emphasis; problem solving responsibilities.
Skills	Range and level	problem solving ability of operators, staff, and managers.
	Availability	compatibility of skill to new tasks.
	Upgradibility	training & retraining requirement.
Management Systems	Retraining	frequency, scope & formality.
	Appraisal & Incentives	individual or team orientation in performance appraisal.
	Supervision & Control	closeness of decision making authority to trouble spots.
	Planning & Accounting	long term or short term focus; activity or labour based costing.
Integration & Culture	Communication format	emphasis on formal or informal channels of communication.
	Co-ordination	concurrent or sequential based cross-functional activity norm
	Participation	degree of employee motivation and empowerment for decision making
	People policy	displacement vs relocation practices accompanying factory automation

III) Resources as an Influencing Factor

The purpose of long term strategic planning for manufacturing capability build-up is to relax the capability constraints. Accomplishment of this purpose, however, is subject to current resource constraints. Two critical resources for implementation of AMT are capital and time, as shown in Fig.4-5, and in Table 4.4 below:

Table 4.4 Resource Factor and the Components

Resource Factor Sub-Components and Elements	
Capital	Initial investment capital
	Training and Personnel funds
Access to AMT expertise	Internal source
	External source
Time for implementation	Project completion period
	Productivity disturbance period

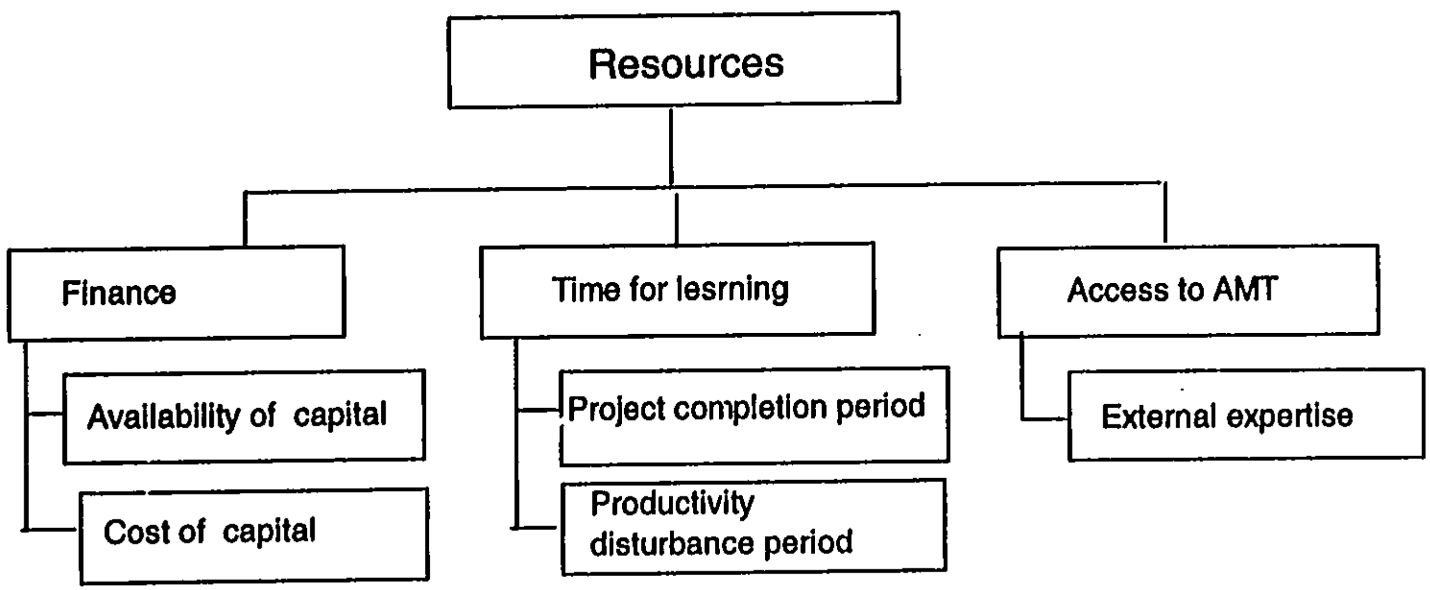


Fig. 4-5 Resource Factor Components

Time as a resource constraint for AMT project implementation is particularly critical when the advances in new technology shorten the effective life span of a particular piece of technology [**Stalker,** 1994; **Sonnenberg,** 1994]. Disturbance of productivity during the transition period represents a type of opportunity cost of upgrading programs. [**Kennedy,** 1993].

4-3. Method for assessing Goal-Factor interdependence:

As stated before, the Impact Priority of factors can be obtained by the Eigen vector method, which is developed by Saaty as essential part of AHP analysis [**Saaty,** 1980,1982]. A brief description of the Eigenvector method is given below.

Factor interdependence in Fig.4-2 can be expressed as a direct reachability matrix **A** (assume one-way interdependence of Capability on the influencing factors; a node reaches itself by a loop):

		C1 (Cap)	C2 (Org)	C3 (Tech)	C4 (Reso)
	Cap (C1)	1	0	0	0
A =	Org (C2)	1	1	1	1
	Tech (C3)	1	1	1	1
	Reso (C4)	1	1	1	1

4-3-1) <u>Pairwise comparison</u>: The interaction among the cluster of factors are determined by conducting pairwise comparisons of the cluster components with respect to the heading component of each column block, wherein a component has an entry 1 in that column. For example, the pairwise comparisons associated with the column block C1 in the reachability matrix **A** above is the following relative impact priority matrix **A1**:

A1 =

Column Block Cap (C1)	C1	C2	C3	C4	Eigenvector $e^{(C1)}$
C1	1	a_{12}	a_{13}	a_{14}	$e_1^{(C1)}$
C2	a_{21}	1	a_{23}	a_{24}	$e_2^{(C1)}$
C3	a_{31}	a_{32}	1	a_{34}	$e_3^{(C1)}$
C4	a_{41}	a_{42}	a_{43}	1	$e_4^{(C1)}$

In the matrix the element a_{ij} is the relative impact priority of cluster Ci over Cj when their impact weights with respect to the cluster C1 are compared.

If e_{i1} and e_{j1} represent the absolute impact weight that cluster Ci and Cj have on the cluster C1, respectively, then

$$a_{ij} = e_{i1}/e_{j1}. \qquad e_{j1} \neq 0$$

Note that a_{ij} and a_{ji} are assumed to be reciprocal with each other, in order to maintain the consistency of the comparison. Also note that the reciprocity between a_{ij} and a_{ji} is maintained notwithstanding the reachability of the cluster factors Ci and Cj in the overall hierarchy.

The quantitative scoring of a_{ij} can be made on two grounds:

a) *Subjective Judgement* of relative importance of two items;

Saaty suggested a subjective comparison scale, as Table 4-5:

Table 4-5. The Pairwise Comparison Scale [Saaty, 1980, 1982]

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two activities contribute equally to the objective
3	Weak importance of one element over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance of one over another	Experience or judgement strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above nonzero	If aij = 1/aji when aji is one of the nonzero values above	A reasonable assumption
Rationals	Ratios arising from the scale	If consistence were to be forced by obtaining n numerical values to span the matrix

The subjective scale can be applied to evaluate qualitative criteria. Saaty stated that the reasonable number of items that could be simultaneously compared by the human brain was 7±2. [Saaty, 1980]. Consistency in judgements can be measured with a Consistency Index (CI) and Consistency Ratio (CR), to be described below.

b) *Objective Measures* of attribute values of the two items.

Critics of the subjective scale pointed out two problems associated with the 1-9 integer scale: i) The scale is easily misused; (ii) Application of the scale fails to preserve valid quantitative performance data (physical and financial measures). A modified method is suggested to combine subjective weighting with ratios of valid quantitative measures of the items under comparison. [**Weber**, 1991]. Assuming that such combination improve the accuracy of the comparison output, in the methodology developed in this thesis both subjective rating scales and quantitative data are to be used for deriving relative weights.

4-3-2) Eigen vector method:

The Eigen vector $\{e_i^{(C1)} | i=1,2,3,4\}$ of the relative impact matrix **A1** is a non-null vector corresponding to the maximum Eigenvalue of the matrix **A1** associated with the cluster C1. That is, if **A1**$=\{aij | i=1..m; j=1..m\}$ is an mxm matrix and $\mathbf{e}^{(C1)}$ is a column vector of mx1, then:

$$\mathbf{A1} * \mathbf{e}^{(C1)} = \lambda_{max} * \mathbf{e}^{(C1)}$$

where λ_{max} is the maximum of all the Eigenvalues of the matrix **A1**, that is:

$$\lambda_{max} = \max \{\lambda_i | \det(\mathbf{A1} - \lambda_i I) = 0, \ i=1,2..m\}.$$

The Eigen vector represents the weight, or impact priority of the cluster factors Ci on the cluster of capability objectives C1. The elements $e_i^{(A1)}$ of this vector are the master weights for the sub-components within each cluster Ci.

4-3-3) <u>Consistency Index (CI) and Consistency Ratio (CR)</u>:
Deviation from pairwise comparison consistency can be measured by the two metrics: CI and CR.

$CI = (\lambda_{max} - m)/(m-1)$

and $CR = CI/RI$

where m = number of items compared in the matrix

RI = Random Index of mxm matrix

= CI of a randomly generated reciprocal matrix from the scale 1-9, with reciprocals forced.

A set of RI based on 500 sample simulation follows:

m	3	4	5	6	7	8	9	10	11
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

If $CR \leq 0.10$, then the judgement is accepted as consistent. Carrying the pairwise comparisons onto the sub-components within each cluster factor will subsequently establish the impact priorities for the components with respect to their parent cluster.

The main concerns in this thesis are the impact priority $e^{(C1)}$. Analysis can be extended in a similar way to each column to obtain the Eigenvectors $\{e_i^{(C2)}\}$, $\{e_i^{(C3)}\}$ and $\{e_i^{(C4)}\}$. For example:

	Column Block Org (C2)	C2	C3	C4	Eigenvector $e^{(C2)}$
	C2	1	a_{23}	a_{24}	$e_2^{(C2)}$
A2 =	C3	a_{32}	1	a_{34}	$e_3^{(C2)}$
	C4	a_{42}	a_{43}	1	$e_4^{(C2)}$

4-4. The Second Level Factor Impact Priority Weighting

Within each cluster of factors in Fig.4-2 the hierarchies of sub-components are shown in Fig.4-3 to 4-5, and Table 4-1 to 4-4. The interactions between the sub-components within the same cluster can also be expressed by the reachability matrices similar to that of the matrix A above.

One critical objective is to obtain the interdependence weights of the sub-components in technological factor with respect to their peer sub-components they interact with. The interactions may have different interpretations in different cluster sub-hierarchies. In the Technological base cluster, eg., the interaction impact may represent the precedence or supportive effect of one subelement to another. When no interaction is assumed for a pair of sub-components, the entry in the reachability matrix is zero. Identification of interdependence in this way may facilitate a comprehensive consideration in design of technological upgrade programs.

4-5. Interdependence between components of different clusters

Matrices can also be constructed to conduct the pairwise comparisons between sub-components in one cluster with respect to their interdependence on components in other clusters, and Eigenvectors so obtained can be used as the second level impact priority weights of the sub-components with respect to a criterion component in another cluster. For simplifying the analysis, only the interdependence of Technological factor on Organisational factor is to be dealt in weighing the critical technological upgrading alternatives (ie. weights in ORGADJUST criterion in the Chapter 6).

4-6. Possibility for extending the analysis scope

The interdependence weights that critical technological upgrading alternatives have on the organisational and resource factors may indicate the necessary changes in these factor components. The feasibility of such changes are determined by the interactions of the Level 3 factors (Actors) in Fig.4-1. Completing the forward AHP analysis may generate the projection of the likely outcome of the capability building programs, expressed in the form of weights of possible scenarios at the level 6. As stated earlier, however, such analysis is outside the scope of the present thesis. The focus here is on the top two levels of the hierarchy only.

4-7. Summary of the chapter

In this chapter, description of influencing factors of the capability upgrading process are given in generic terms, together with a discussion of the AHP method for assessing the impacts among the factors. Detailed discussion on using an AHP based method to analyze technological factors for identifying upgrading priorities will be the given in the next chapter.

Chapter 5.

Identify Critical Area In Technological Factor

In the Capability Improvement Process outlined in the Fig.3-1, the steps for establishing the strategic goals and performance objectives are followed by identification of the critical technological areas that are most inadequate for supporting the desired manufacturing objectives. This task can be done by performing a forward AHP analysis concerning only the top two levels of the hierarchy of Fig.4-1. The top two levels of the Fig.4-1 are expanded here into Fig.5-1 for detailed analysis. It is very likely that the weakest link in performance capability is not due to technological but organisational factors. While it is desirable to be able to identify such a scenario of valid managerial concern, it will not be the focus of this thesis.

5-1. Identify Critical Technological Area by AHP

In Fig.5-1, the top level of the hierarchy is the desired manufacturing capability. The second level consists of the four strategic goals identified in the chapter 3:
Goal={Cost(G1), Quality(G2), Flexibility(G3), Delivery(G4)}.

Level Three lists the operational objectives associated with each of the four goals, respectively. Level Four decomposes

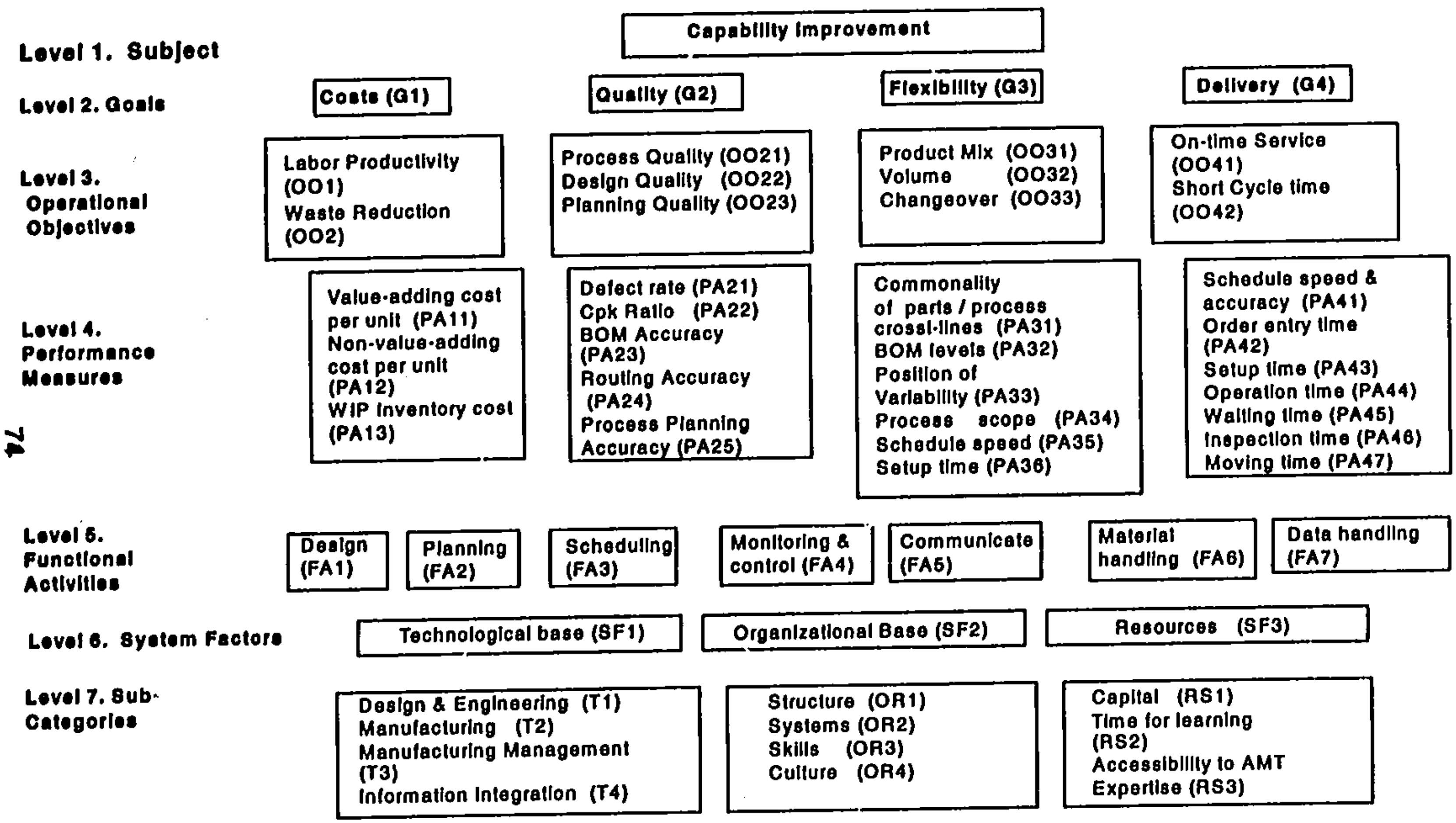


Fig. 5.1. FORWARD PLANNING AHP

the operational objectives into more specific performance measures. Level Five consists of major functional activities, extracted from Table 3-2, that drive the performances:

Activity = {Design(FA1), Planning&scheduling(FA2), Processing(FA3), Monitoring&control(FA4), Communication(FA5), Material handling(FA6), Data-handling(FA7)}.

Level Six contains the three influencing factors that determine the effectiveness and efficiency of executing the activities. Note that there is direct correspondence between the Fig.5-1 and Table 3-2.

Level Seven consists of the subcomponents in each factor, corresponding to Tables 4-1, 4-2 and 4-4.

A Level Eight can be added to the hierarchy to list the possible improvement program candidates. Carrying out the AHP analysis through this 8-level hierarchy may lead to selection of the most desirable candidate, in the form of the highest weighted one among the capability improvement programs. Alternatively, the composite weights (eigenvectors) of the factors and of the technological areas generated from the AHP analysis of levels 1-7 can be used as the weight coefficients of decision variables for mathematical programming formulation and solution, as will be discussed later.

With respect to the prioritized goals (Level 2) and operational objectives (Level 3), the aspects of performances (Level 4) are weighed by the pairwise comparison with respect to their parent objectives. In this level it may be possible to adopt objective quantitative data as the basis for pairwise comparison, in place of the 1-9 subjective scale. Activities of Level 5 are weighed against the performance measures to allocate shares of causal effect responsibility. In turn, technology, organization and resources factors of Level 6 are weighed with respect to their impact on the activity execution. Within the technological factor, the critical area is identified in terms of the highest composite weight.

A complete assessment of peer element interdependence on one another may be conducted by the method described in Chapter 4. To reduce the dimensions of the analysis, a simplifying approach is adopted: weigh the peer elements according only to their relative impact on the higher level criteria, without considering peer element interdependences. Table 5-1 presents the components in every level and weights of each component local to that level. It should be noted that the structure of the hierarchy is not rigid. The levels and components may be changed as per specific situations being analyzed, as to be shown in Chapter 7.

Table 5-1. Hierarchy Components and Weights

Level 2 Goals	Level 3 Operational Objectives	Level 4 Performance Aspects	Level 5 Functional Activities	Level 6 System Factors	Level 7 Category
G1 (wg_1)	OO11 (woo_{11}) OO12 (woo_{12})	PA11 (wpa_{11}) PA12 (wpa_{12}) PA13 (wpa_{13})	FA1 (wa_1)	SF1= Tech (wsf_1)	T1 (wt_1) T2 (wt_2) T3 (wt_3) T4 (wt_4)
G2 (wg_2)	OO21 (woo_{21}) OO22 (woo_{22})	PA21 (wpa_{21}) PA22 (wpa_{22}) PA23 (wpa_{23}) PA24 (wpa_{24})	FA2 (wa_2) FA3 (wa_3)	SF2= Org (wsf_2)	Org1 (wor_1) Org2 (wor_2) Org3 (wor_3) Org4 (wor_4)
G3 (wg_3)	OO31 (woo_{31}) OO32 (woo_{32}) OO33 (woo_{33})	PA31 (wpa_{31}) PA32 (wpa_{32}) PA33 (wpa_{33}) PA34 (wpa_{34}) PA35 (wpa_{35}) PA36 (wpa_{36})	FA4 (wa_4) FA5 (wa_5)	SF3= Reso (wsf_3)	Res1 (wrs_1) Res2 (wrs_2)
G4 (wg_4)	OO41 (woo_{41}) OO42 (woo_{42})	PA41 (wpa_{41}) PA42 (wpa_{42}) PA43 (wpa_{43}) PA44 (wpa_{44}) PA45 (wpa_{45}) PA46 (wpa_{46}) PA47 (wpa_{47})	FA6 (wa_6) FA7 (wa_7)		Res3 (wrs_3)

The four strategic goals $\{Gi \mid i=1..4\}$ in Level 2 are assigned with priority **WG**$=(wg_1, wg_2, wg_3, wg_4)$ by pairwise comparison. The level 3 operational objectives $OO=\{OO_{ij} \mid i=1,2,3,4; j=1,2..j(i)\}$ under each Gi, are assigned with weights **WOO**$=\{woo_{ij} \mid i=1,2,3,4; j=1,2..j(i)\}$, and the Level 4 performance aspects **PA**$=\{PA_{ih} \mid i=1,2,3,4; h=1,2..h(i)\}$ with **WPA**$=\{wpa_{ih}\}$, against their parent level, respectively. wpa_{ih} is computed as:

$$wpa_{ih}=\sum_{j=1}^{j(i)} woo_{ij} * wpa_{jh}^{(i)} \qquad \forall i,h \qquad (5.1)$$

Also, the major activities **FA**=$\{FAl|l=1,2..7\}$ in Level 5 are weighed against the performances $\{PAih\}$, and composite weights **WA**=$\{wa_l|l=1,2,..7\}$ obtained through the matrices as follows:

Activities **FA**	G1 (wg_1) PA1h (wpa_{1h})	G2 (wg_2) PA2h (wpa_{2h})	G3 (wg_3) PA3h (wpa_{3h})	G4 (wg_4) PA4h (wpa_{4h})	Composite Weight **WA** $=\{wa_l\}$
FA1	wa_{11}	wa_{21}	wa_{31}	wa_{41}	wa_1
FA2	wa_{12}	wa_{22}	wa_{32}	wa_{42}	wa_2
FA3	wa_{13}	wa_{23}	wa_{33}	wa_{43}	wa_3
FA4	wa_{14}	wa_{24}	wa_{34}	wa_{44}	wa_4
FA5	wa_{15}	wa_{25}	wa_{35}	wa_{45}	wa_5
FA6	wa_{16}	wa_{26}	wa_{36}	wa_{46}	wa_6
FA7	wa_{17}	wa_{27}	wa_{37}	wa_{47}	wa_7

The columns are the impact weights wa_{lh} of each activity FAl with respect to the column head goal (PAih), derived by the Eigenvector method. The weight vector (right hand column) **WA** = $\{wa_l|l=1,2,..7\}$ is computed from the equation (5.2).

$$wa_l=\sum_{i=1}^{4} wg_i\,[\sum_{h=1}^{h(i)} wpa_{ih} * wa_{hl}] \qquad \forall l \qquad (5.2)$$

For System Factors **SF**=$\{SF1, SF2, SF3\}$ in Level 6, the weights **WSF**=$\{wsf_1, wsf_2, wsf_3\}$ are calculated from the equation (5.3):

$$wsf_v=\sum_{l=1}^{7} wa_l * wsf_{lv} \qquad v=1,2,3 \qquad (5.3)$$

The elements of **WSF** indicate the relative impact priority of the three system factors for capability improvement. They will be needed if the AHP analysis is to be carried out further down the hierarchies of Fig.4-1. For critical technological area identification, however, only the SF1 is of concern, ie., SF2 and SF3 can be skipped by setting wsf1=1. This means that the Level 6 in Fig.5-1 and Table 5-1 can be bypassed for the present analysis.

Therefore, to diagnose the priority area within Technological factor SF1, Level 7 cluster $\{Tk|k=1,2,3,4\}$ should be evaluated by pairwise comparison directly against the Functional Activities **FA** of Level 5, so as to obtain the priority vector **WT** = $\{wt_k|k=1,2,3,4\}$. Impact weight matrix **WT** can thus be constructed for technological factor components T = $\{Tk|k=1,2,3,4\}$, (refer to Table 4-1), as the following:

Matrix WT	FA1 (wa_1)	FA2 (wa_2)	FA3 (wa_3)	FA4 (wa_4)	FA5 (wa_5)	FA6 (wa_6)	FA7 (wa_7)	Weight $\{wt_k\}$
Enginring Tool (T1)	wt_{11}	wt_{21}	wt_{31}	wt_{41}	wt_{51}	wt_{61}	wt_{71}	wt_1
Manufg Tool (T2)	wt_{12}	wt_{22}	wt_{32}	wt_{42}	wt_{52}	wt_{62}	wt_{72}	wt_2
Manufg Mgt Tool (T3)	wt_{13}	wt_{23}	wt_{33}	wt_{43}	wt_{53}	wt_{63}	wt_{73}	wt_3
Info.Integr ation (T4)	wt_{14}	wt_{24}	wt_{34}	wt_{44}	wt_{54}	wt_{64}	wt_{74}	wt_4

The columns $\{wt_{lk}\}$ in the matrix are the weights (Eigenvector) of each technological area Tk with respect to the column heads (Activity Al). The right hand column gives the composite weight of the technological areas, by Equation (5.4) as:

$$wt_k=\sum_{l=1}^{7} wa_l * wt_{lk} \qquad \forall k \qquad (5.4)$$

This gives the priority weights of Tk when the Technological factor is considered alone, ie., when $wsf_1=1$.

The line of questions to be asked in conducting the pairwise comparisons should emphasize the relative criticality of the technological areas. For example: "How many times is the Engineering design facility more inadequate than the manufacturing facility with respect to supporting the activity?" Outcome of the comparisons indicates the critical area within the Technological base, in terms of the highest impact priority weight.

5-2. Critical Elements Within Each Technological Area

Subcomponents **TEk** in a technological area Tk are further weighted to identify the critical subareas. Suppose the T2 (Manufacturing facility) is the critical area with $wt_2 = \max \{wt_k | k=1,2,3,4\}$, critical elements TE2p in the T2 area can in turn be identified. This is achievable with a priority matrix $WTE=\{wte_{kp}\}$ similar to WT, with the left hand column composed of subelements of T2 area: **TE2**$=\{TE2p|p=1,2,3\}$. (Table 4-1b).

FA_l (l=1,2...L)	TE21	TE22	TE23	Local Weight $\{wte^{(l)}_{2p}\}$
Processing h/w&s/w (TE21)	1	e12 = wte21/ wte22	e13 = wte21/ wte23	$wte^{(1)}21$
MH&S Tool (TE22)	e21 = 1/e12	1	e23 = wte22/ wte23	$wte^{(1)}22$
Data Handling (TE23)	e31 = 1/e13	e32 = 1/e23	1	$wte^{(1)}23$

The entries in the columns are pairwise comparison scores of the T2 elements with respect to the Functional Activities {FAl¦l=1.2..7}, respectively. The right hand column again gives the local weight of each T2 element with respect to FA_l. In general, composite weights of TEkp will be given by:

$$wte_{kp}=\sum_{l=1}^{7} wfa_l * wte^{(l)}{}_{kp} \qquad (5.5)$$

The line of questions to be asked in conducting the pairwise comparison may be: "How many times is the element TEkp more inadequate than the element TEkq for supporting the activity in question?" The highest weighted element **TEkp*** is designated as the critical element for upgrading attention.

5-3. Identify Critical Path ---A Possible Extension

Following identification of the critical area and critical elements within the critical area, it is imperative to determine the critical path, ie., the upgrading phases and stepstones that lead to closing performance capability gaps.

Two limiting states of the critical element can be established: the equipment on hand, and the ideal equipment with performance capability beyond the state-of-the-art technology. Between the two limits there may be a series of intermediate scenarios, or embodiments of the critical element, representing the incremental improvement of the required performance capability. These information are assumed to be obtainable from relevant database of technology, eg., vendors' information package, R&D reports, and benchmarks.

The priority weights of candidate items may be derived from subjective evaluation, ie., Eigenvector method, or from the ratio of physical measures of the performance capabilities of each pair of items. In the latter method, for example, if Product Flexibility is the desired goal, equipment candidates may be compared on the criteria of scope of operations, average setup time, etc., with actual data in place of the subjective rating. The modified AHP methodology proposed by **Weber** [1991] is applicable to this level of comparison.

When capital costs associated with equipment candidates are considered together with tangible benefits of possible performance improvement, a benefit-cost ratio (BCR) can be computed for each candidate. The conventional approach of selecting the candidates on the ground of benefit-cost ratio would conclude decision making at this stage by picking up the candidate with the highest BC ratio.

The holistic planning approach of capability building process, on the other hand, must take into account the cross impacts of selecting certain technological solutions on other factors, in particular the organisation and resources. Implementation feasibility has to be predicted. The proposition is that the degree of feasibility is path dependent. Therefore, the task beyond the conventional tangible benefit-cost ratio analysis is to identify the feasible as well as critical path.

The meaning of critical paths in this context may be different from the classical definition of the concept, which is based on the least amount of available slack in project execution. The critical path in implementing a technological solution for the capability improvement may be defined as a series of change programs in both technological areas and organizational areas, upon which the desired outcomes are built step by step. These change programs are human as well as technological oriented; hence the relevance of the factors of Levels 3 to 6 in the Fig.4-1.

The complete planning cycle should consist of both forward planning and backward planning processes [Saaty, 1980, 1982].

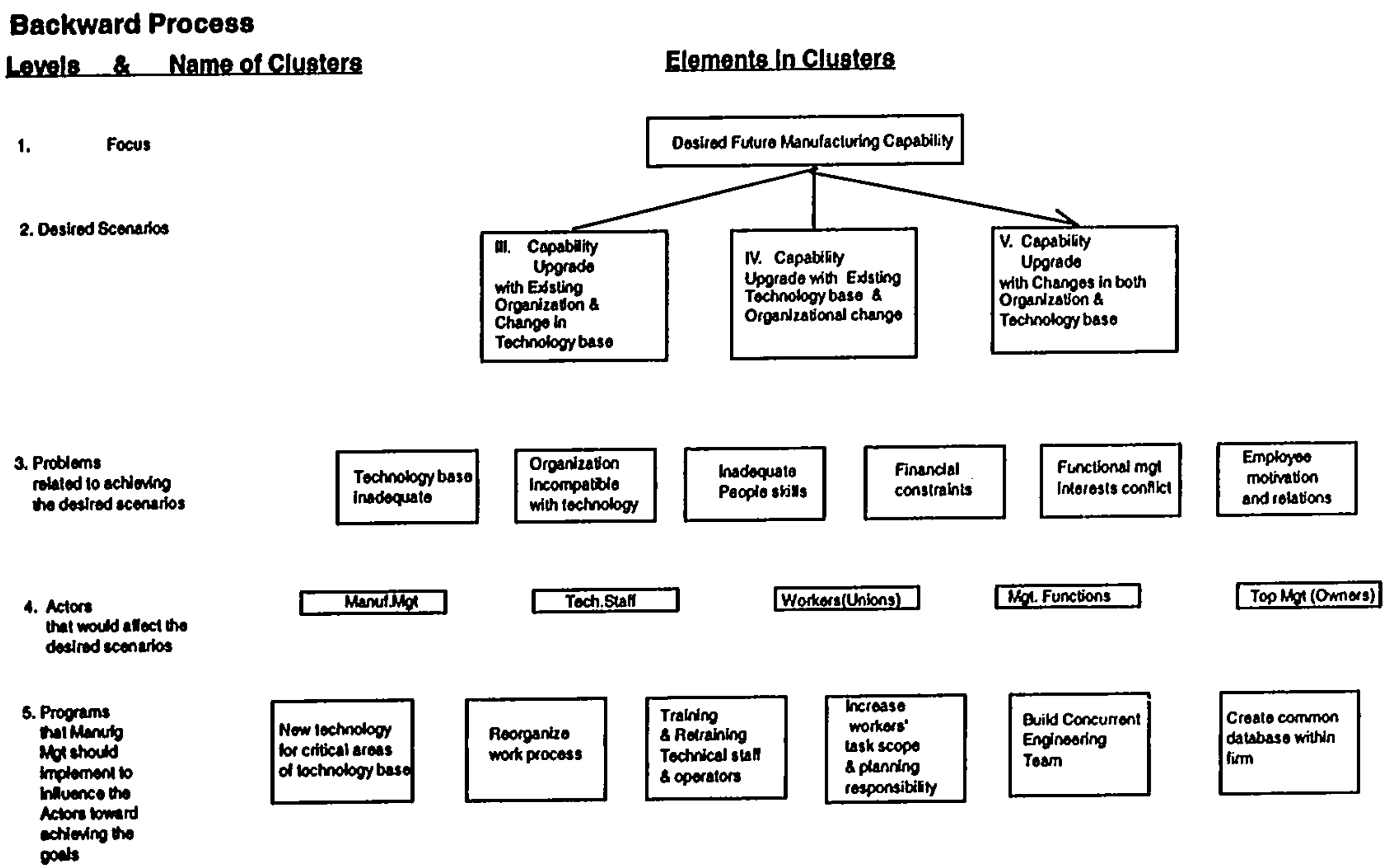


Fig.5-2 Backward Process

Fig 5-2 is a backward planning hierarchy. Such complete cycles will, however, involve extensive consideration of managerial and organizational issues which are not within the focus of this thesis, and are hence only mentioned here in outline. Conformity of implementation of the chosen technological programs to aspects of the organization may be checked in terms of Compatibility, as shown in the matrix below.

Upgrading focus, by TEkp	ORG1 (wor_1)	ORG2 (wor_2)	ORG3 (wor_3)	ORG4 (wor_4)	Weight
TEkp1	$wtor^{(1)}_{kp1}$	$wtor^{(2)}_{kp1}$	$wtor^{(3)}_{kp1}$	$wtor^{(4)}_{kp1}$	$wt^{(or)}_{kp1}$
TEkp2	$wtor^{(1)}_{kp2}$	$wtor^{(2)}_{kp2}$	$wtor^{(3)}_{kp2}$	$wtor^{(4)}_{kp2}$	$wt^{(or)}_{kp2}$
TEkp3	$wtor^{(1)}_{kp3}$	$wtor^{(2)}_{kp3}$	$wtor^{(3)}_{kp3}$	$wtor^{(4)}_{kp3}$	$wt^{(or)}_{kp3}$

Relative smoothness in technological changes may be compared with the line of question "How many times is changing TEkpr more compatible than TEkpq with the organizational area?" In similar way, relative pressure on resources by technological change alternatives can be evaluated.

More importantly, potential bottlenecks in the organization to the implementation of the desired technological changes can be predicted by pairwise comparison between ORGq and ORGq' with respect to implementing required changes in the area of TEkp. Let the weights of *Incompatibility* of organizational factors to the desired technological changes be denoted as:

$$\textbf{WORG} = \{worg_{\epsilon\theta} \mid \epsilon=1,2,3,4;\ \theta=1,2,..\theta(\epsilon)\},$$ where,

each $worg_{\epsilon\theta}$ can be obtained from the matrix below:

ORG elements	TE1 (wte_1)	TE2 (wte_2)	TE3 (wte_3)	TE4 (wte_4)	Weight **WORG**
ORG11	$worg^{(1)}_{11}$	$worg^{(2)}_{11}$	$worg^{(3)}_{11}$	$worg^{(4)}_{11}$	$worg_{11}$
ORG12	$worg^{(1)}_{12}$	$worg^{(2)}_{12}$	$worg^{(3)}_{12}$	$worg^{(4)}_{12}$	$worg_{12}$
:	:	:	:	:	:
ORG$\epsilon\theta$	$worg^{(1)}_{\epsilon\theta}$	$worg^{(2)}_{\epsilon\theta}$	$worg^{(3)}_{\epsilon\theta}$	$worg^{(4)}_{\epsilon\theta}$	$worg_{\epsilon\theta}$

The inside columns in the above matrix are the eigenvectors obtained from the pairwise comparison matrices of ORG elements with respect to the column head (Technological areas to which upgrading is to be implemented), with the line of questions like "How many times is $ORG_{\epsilon\theta}$ less fit than $ORG_{\epsilon'\theta'}$ for accepting changes in it due to changes in the technological area". The composite weight vector of the organizational elements, the right hand column, consists of the elements which are the weighted sum of elements in each row in the above matrix, ie.:

$$worg_{\epsilon\theta}=\sum_{k=1}^{4} wte_k x worg_{\epsilon\theta}^{(k)} \qquad \forall\epsilon,\theta \qquad (5.6)$$

These weights represent the levels of *possible resistance* of an organizational area to technological changes, and can be defined as the coefficients of *"Riskiness to change"* in the final decision criterion of organizational adjustment, *ORGADJUST*, to be discussed in Chapter 6.

Repetition of the line of questions down the levels of the Fig.4-1 shall generate the likelihood of outcomes of the technical program implementation. Unfavourable rating of desired outcomes indicate the necessary adjustment in controllable factors, or intervention by the firm's management in other areas. This triggers a backward process, illustrated in the Fig.5-2. If desired outcomes can not obtain the required priority rating after the iteration with the chosen technological solution, its feasibility becomes doubtful. Thus the solution has to be changed and another round of forward process starts with newly designed technological programs.

5-4. Summary of the chapter

Hierarchical structuring of capability influencing factors is presented. Assessing the interdependence between the clusters of factors, including the strategic objectives, functional activities, technological bases and other influencing factors are attempted by the AHP method. The components in the hierarchy (Table 5-1 and Fig.5-1) are not restrictive but for illustration and discussion purposes only. The number of levels and the number of factors within any level may vary according to the actual situation under analysis, as will be shown in the case study in Chapter 7.

The Eigenvector method in the AHP is used as the basic method for deriving composite weights of impact-priority of factors. While it is possible to carry out the entire analysis of critical area identification and alternative program selection using AHP alone, as documented in the literature (see, eg., **Boucher&MacStravic** [1991], **Weber** [1993], **Liberatore et al** [1992], **Basu et al** [1994], etc.), this thesis takes an alternative approach in synthesizing the cross-impacts of the multiple factors on the decisions about capability upgrading programs. The rationale behind this alternative approach can be stated as following:

a) The priority weights of alternatives, expressed as eigenvectors, do not explicitly convey the objective information of capability improvement potential (eg., % gap closure), and are therefore less suitable for program justification than for alternative selection;

b) To make full use of this objective information about a program's capability improvement potential, one can combine the information with the priority weights of the capability measures in the final synthesis stage of multi-criteria decision making. The method will be discussed in detail in the next chapter.

Chapter 6.

Synthesis Method for Multi-Criteria Decision Making

While the previous AHP based analyses lead to identification of critical areas for improvement, selecting the appropriate improvement programs is the focus of this chapter. The multiple-factor interdependence inherent in the manufacturing performance capability building, as shown in the Fig.4-1 and Fig.5-1 earlier, dictates the need for multiple criteria decision making (MCDM) approach for this task. The priority weights of the manufacturing objectives and influencing factors obtained from the forward analytic hierarchy process (AHP), described in previous chapters, shall be used as the coefficients for the set of decision variables to be defined below. The AHP may also be used to prioritize the set of goals to be formed and satisfied in this stage.

6-1. Multiple Goal Formulation

Zeleny [1982] defines that a Goal is a temporarily fixed requirement that is to be satisfied as closely as possible in a given problem formulation. An objective is an unbounded, directionally specified (max or min) requirement which is to be followed to the greatest extent possible.

In the context of capability building, objectives may be set by actors in the hierarchy of Fig.4-1, pertaining to different clusters of factors. Without limiting the range of objectives in real cases, the following objectives are set to aid the present discussion:

Objective 1: Maximize composite improvements of performance capability in the basic dimensions (eg., Cost, Quality, Delivery, Flexibility).

Objective 2: Maximize returns on investment (capital assets and training) measured by DCF methods (eg., IRR) for the technological upgrading programs in the planning period.

Objective 3: Minimize disturbance to production process, in terms of project completion time and productivity disturbance period associated with technological upgrade programs.

Objective 4: Minimize possible organisational resistance to organizational changes accompanying technological programs.

Define the following decision indices:

Alt_r = Technological upgrade alternative r. r=1,2,3...R.

$$X_{kp0r} = \begin{cases} 1, & \text{if Alt\_r includes upgrading TEkp} \\ 0, & \text{if otherwise} \end{cases}$$

The task is to select the appropriate alternative, Alt_r*, from the set of candidates {Alt_r|r=1,2...} to strike the optimal balance between these objectives, given their ranks of priority. Compromise Programming approach [**Zeleny**, 1982] is adapted for this task, as outlined later.

6-1-1) Parameters relating to Objective 1:

Let G = {Gi|i=1,2,3,4}

= Generic manufacturing objectives as in Chapter 5

= {Cost, Quality, Flexibility, Delivery}

WG = $\{wg_i | i=1,2,3,4\}$ = Priority weight vector for G, to be input by decision makers in the firm

PA = $\{PA_{ih} | i=1..4;\ h=1..h(i)\}$

= Performance objectives as in Chapter 5

WPA= $\{wpa^{(ih)} | \forall i,h\}$ = Priority weights of performance objectives PA_{ih} with respect to Gi, by Equation 5-1.

T = {Tk | k=1,2,3,4}

= Manufacturing base technological areas

= {Engineering, Manufacturing, Manufacturing Management, Information Integration}

$WT^{(ih)} = \{wt^{(ih)}_k | k=1,2,3,4\}$ = Priority weight vector for Tk with respect to supporting objectives in PA_{ih}

$TEk = \{TEkp | k=1,2,3,4;\ p=1,2,3...p(k)\}$

= Member set of technological area Tk, (as in Fig.4-3)

$WTEk = \{wte^{(ih)}_{kp} | p=1,2...p(k),\ k=1,2,3,4\}$

=Weights of tekp contributions with respect to PA_{ih}

These weights can be derived using AHP, as in Chapter 5.

Further, let:

$M^{(ih)}_r$ =PA_{ih} related performance capability measure of state (program candidate) r, r=0,1,2...u

where r=0 denotes the as-is state of the system;

r=u denotes the target state, the upper bound, or ultimate level of performance in PA_{ih}

$D^{(ih)}_{0r}$, the Absolute Improvement level in PA_{ih} due to upgrading system from state 0 to r, is computed by:

$$D^{(ih)}_{0r} = [\ M^{(ih)}_r - M^{(ih)}_0\ ] \qquad (6.1)$$

$d^{(ih)}_r$, the Improvement Rate (%) in PA_{ih} from state 0 to r with respect to the desired upgrading step 0 to u, is calculated by equation 6.2 as:

$$d^{(ih)}_r = D^{(ih)}_{0r} \,/\, D^{(ih)}_{0u}$$

$$= [M^{(ih)}_r - M^{(ih)}_0] / [M^{(ih)}_u - M^{(ih)}_0] \qquad (6.2)$$

$D^{(ih)}_{0u}$ in the denominator reflects the *capability gap* in the performance objective PA_{ih}, with respect to the objective Gi. These may be hypothetical as well as real measures, used as the yardstick for capability upgrading. The intermediate stages denoted by $d^{(ih)}_{r}$ embody the alternative programs, and are of major interest. The values of these measures need to be established by intensive analysis in each real case.

6-1-2) Parameters relating to Objective 2:

C^r_0 = Initial cost ($) of the upgrading program Alt_r.

E^r_n = Annual net cash flow ($) in year n, expected from the upgrading program Alt_r.
where n=1,2..N(r), the life of Alt_r

MARR = Hurdle rate (%) used by the firm for capital budgeting in AMT acquisition during the planning period. The rate may be arbitarily set at a high figure.

6-1-3) Parameters relating to Objective 3:

τ_r = Time to implement Alt_r in the firm {eg., work days} estimated as the time for the longest path of Alt_r

Ω_r = Learning period after implementing Alt_r

Timebase = Arbitary time period, eg., total working days per month, used as the unit measure of time requirements.

6-1-4) Parameters relating to Objective 4:

$ORG = \{ORG_{\epsilon\theta} \mid \epsilon=1,2,3,4;\ \theta=1,2..\theta(\epsilon)\}$

= Organization Factor elements as in Fig.4-5

$WORG_{\epsilon\theta}$ = "Riskiness to Change" weights of $ORG_{\epsilon\theta}$, $\forall\epsilon,\theta$, (with respect to criterion of resistance level in adjusting $ORG_{\epsilon\theta}$, as to be required by adapting to the changes in TEkp during implementation of Alt_r, see Chapter 5 for its original definition)

6-1-5) Transformation of Objectives (1-4) to Goals

The order of magnitude of the set of objectives (1-4) needs to be commeasurable in order to be treated together. Thus they are transformed to Goals, with given target values and relative scales, as follows:

Goal1: $CAPAGAIN\_r^* = \max\ \{CAPAGAIN\_r \mid \forall r\}.$ (6.3)

Goal2: $RETURN\_r^* = \max\ \{IRR\_r \mid \forall r\}.$ (6.4)

Goal3: $TRANSITION\_r^* = \min\ \{TRANSITION\_r \mid \forall r\}.$ (6.5)

Goal4: $ORGADJUST\_r^* = \min\ \{ORGADJUST\_r \mid \forall r\}.$ (6.6)

where the relevant decision criteria are defined as follows:

$$CAPAGAIN_r = \sum_{i=1}^{4} wg^{(i)} \{ \sum_{h=1}^{h(i)} wpa^{(ih)} d_r^{(ih)} \}. \qquad \forall r \qquad (6.7)$$

The IRR is the discount rate that satisfies the following discounted cash flow equation:

$$0 = -C_0^r + \sum_{n=1}^{N(r)} E_n^r (1+IRR_r)^{-n} \qquad \forall r \qquad (6.8)$$

$$TRANSITION_r = \frac{(\ \tau_r + \sum_{k=1}^{K}\sum_{p=1}^{P(k)} \Omega_{kpor} * X_{kpor}\ )}{TIMEBASE} \qquad \forall r \quad (6.9)$$

$$ORGADJUST_r = \sum_{e=1}^{4}\sum_{\theta=1}^{\theta(e)} worg_{e\theta} * OSI_{e\theta}^{(r)} \qquad \forall r \qquad (6.10)$$

6-2. Explanations about Goals and Decision Criteria

Compromise Programming attempts to satisfy the set of conflicting goals *simultaneously*, as opposed to the Goal Programming approach which assume preemptive weights of one goal over another, and satisfy them in sequence. To achieve the compromise, ideal values of the goals are established, and the composite distances of the goals to the ideal values are to be minimized. This requires that the scales of the concerned goals are in relatively similar order of magnitude; otherwise the solution could be dominated by the goal with a large metric scale. For this purpose, decision criteria in Equation 6.7 to 6.10 need to be expressed in relative measures, so as to be used in Goals 1 to 4. These measures are as follows:

6-2-1) The Criterion from Equation 6.7 calculates the weighted sum of expected capability gains from adopting Alt_r. Since each term in Eqn. 6.7 is expressed as percentage achievement of the performance target, the metric scale of the criterion CAPAGAIN, and that of Goal_1, is [0,1]. The upper bound (ideal value) of the Goal_1 should be 1.

6-2-2) The Criterion from Eqn. 6.8 represents the expected rate of return of Alt_r, in terms of the Internal Rate of Return (IRR); hence the metric scale of Goal2 is percentage points. The ideal value (MARR) of the Goal2 may be arbitarily set such that all the expected IRR_r<MARR; therefore minimizing deviations of the IRR_rs from the ideal value is equivalent to selecting the Alt_r with the maximum IRR_r.

6-2-3) The criterion from Eqn. 6.9 expresses the demand of Alt_r on Time, another valuable resource. The first term in the numerator in Eqn. 6.9 represents the total completion time of Alt_r by its longest route of implementation, by taking the union of implementation time of each sub-elements in Alt_r. The second summation computes the expected disturbance period after putting each sub-element in place. This measurement captures the learning curve effects associated with every technology change [**Kennedy**, 1993]. The completion and learning times may be estimated from past experience, benchmark projects, and detailed engineering and managerial analysis. Typical items may include:

-- site preparation,

--installation,

--test run and adjustment.

--Ω_{kp0r}, the productivity disturbance period due to learning curve effect after project completion should also be included.

Transformation of the scale may be based on the ratio of the total TRANSITION_r to the available timebase in one period (eg., workdays/year). The bound may be difficult to estimate, but since it is the distance from the ideal that matters, one may arbitarily set the bound at 0.1 to begin with, then adjust if necessary.

6-2-4) The criterion by Eqn. 6.10 expresses the degree of incompatibility of Alt_r' to organizational subcomponents (Table 4-3), and indictates the required changes in organization, associated with implementing Alt_r. The metric is derived from quantifying subjective ratings of degrees of Incompatibility of ORG to Alt_r by the Fuzzy Set approach.

The type of factors, $ORG_{\epsilon\theta}$, dictates the necessity of subjective rating to evaluate cross impacts of Alt_r to organizational factors. Subjective rating is prone to vagueness and imprecision. Crisp mathematical models are not capable of handling vagueness of qualitative factors. Quantifying such variables may be attempted by AHP in the form of priority weights assigned to each Alt_r with respect to the level of incompatibility to ORG. However, AHP method only generates relative weights among the Alt_rs. As a planning output, the direct assessment of required level of organizational adjustments would be more desirable. Fuzzy set approach is suitable for this purpose. The fuzzy set treatment is described below.

6-3. Fuzzy set method for quantifying the Goal4

Recall the subjective factors $ORG=\{ORG_{\epsilon\theta} \mid \forall\epsilon,\theta\}$. Here ORG is the Universe.

Let Incompatibility be the attribute of $ORG=\{ORG_{\epsilon\theta} \mid \forall\epsilon,\theta\}$.

$Y=\{Y(ORG_{\epsilon\theta})_r \mid \forall\epsilon,\theta,r\}$ = Degree of Incompatibility of $ORG_{\epsilon\theta}$ to Alt_r.

$Y(ORG_{\epsilon\theta})_r$ be expressed by a set of Linguistic Descriptors = {Little, Slight, Moderate, Significant, Total}

$= \{Y1, Y2, Y3, Y4, Y5\}$.

The fuzzy set of $Y\mu$ of Y is defined by a membership function as:

$$M_{Y_\mu}(Y) \; : \; Y \rightarrow [0,1]. \quad \mu=1,2,3,4,5 \qquad (6.11)$$

The patterns of the membership functions for all Y_μ (μ=1,2..5) can be known to the decision makers from study [**Hirota**, 1993; **Kulkarni et al**, 1994]. Here they are assumed as triangle, and identical for the ORG universe, as shown in Fig 6-1.

The linguistic descriptors can be defined by giving each a fuzzy representation on a 'Universe of Discourse' V:

$V = [0, 0.1, 0.2, 0.3,...0.9, 1]$,

as follows (Y2 = Slight is taken as the example):

$$\text{Slight} = Y2 = [M_{Y2}(x1)/x1, \; M_{Y2}(x2)/x2, ... M_{Y2}(xs)/xs]. \qquad (6.12)$$

where the numerator $M_{Y2}(xs)$ is the degree of membership in Y2 of the value xs, the denominator. $xs \epsilon V$. '/' is the separator, not division operator.

The numerical fuzzy sets of linguistic descriptors are given in Table 6-1:

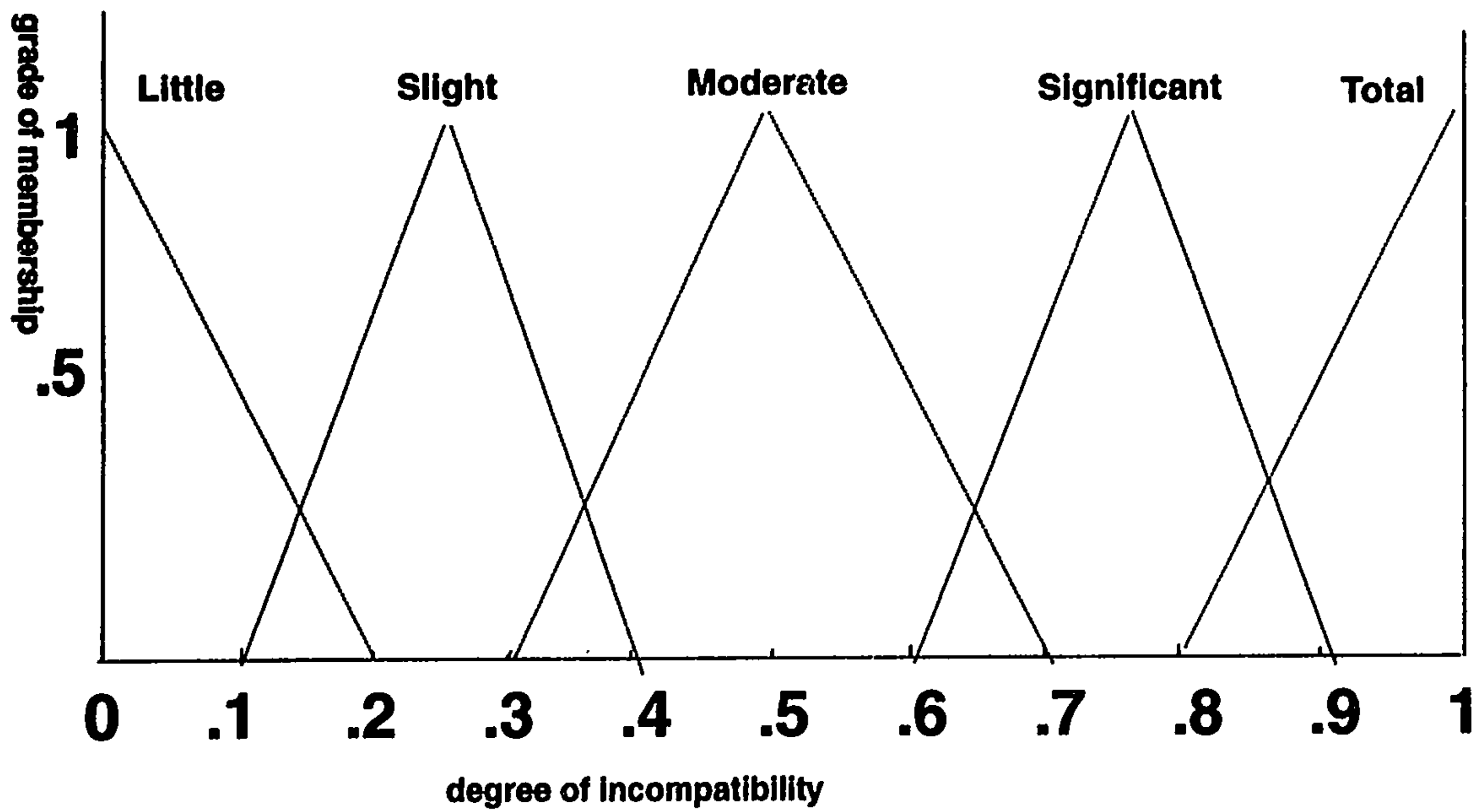


FIG. 6-1. MEMBERSHIP FUNCTIONS OF INCOMPATIBILITY

Table 6-1. Fuzzy membership functions of descriptors

Descriptors	Membership functions $M_{Y_\mu}(x)$	Numerical fuzzy sets
Little (Y1)	1-5x, (0≤x≤.2) 0, for other x	1/0, .5/.1, 0/.2
Slight (Y2)	(20/3)x-2/3, (.1≤x≤.25) 8/3-(20/3)x, (.25<x≤.4) 0, for other x	0/.1, .67/.2, 1/.25 .67/.3, 0/.4
Moderate (Y3)	5x-3/2, (.3≤x≤5) 7/2-5x, (.5<x≤.7) 0, for other x	0/.3, .5/.4, 1/.5, .5/.6, 0/.7
Significant (Y4)	(20/3)X-4, (.6≤X≤.75) 6-(20/3)X, (.75<X≤.9) 0, for other x	0/.6, .67/.7, 1/.75, .67/.8, 0/.9
Total (Y5)	5X-4, (.8≤X≤1) 0, for other x	0/.8, .5/.9, 1/1

For each $ORG_{e\theta}$ in the ORG universe, its degree of incompatibility to Alt_r can be assessed, and a certain subjective rating $Y(ORG_{e\theta})r$ value assigned to it. The Quantified Subjective Index, denoted as QSI, can be calculated as the weighted average in the universe of discourse V, as follows:

$$QSI_{e\theta}^{(r)} = \frac{\sum_{p=1}^{k} M_{Y_\mu}(x_p) * x_p}{\sum_{p=1}^{k} M_{Y_\mu}(x_p)} \qquad \forall \mu, r, e, \theta \qquad (6.13)$$

where the numerator is the summation of products of degree of membership of discrete x_p in $Y\mu$ and the value of x_p on V. The denominator is the sum of the degree of membership of x_p.

For example, suppose ORG31 is rated slightly incompatible (Y2) to Alt_2, then, substitute data from Table 6-1 into Eqn. 6.13:

$$QSI_{31}^{(2)} = \frac{0*.1+.67*.2 + 1*.25 +.67*.3 + 0*.4}{0+.67+1+.67+0}$$

$$= 0.25$$

Obviously, the closer the QSI is to 1, the more organizational changes are required in ORG31 for implementing Alt_2.

The overall level of incompatibility of ORG to Alt_r, ORGADJUST_r, is computed by Eqn. 6.10 as the weighted average of all ORG components' level of incompatibility to Alt_r.

The scale of ORGADJUST is clearly in [0,1]. The ideal value of ORGADJUST for any Alt_r may be 0, indicating complete compatibility. Therefore, for Goal4 one tries to get as close to 0 as possible. A byproduct of the assessment is identification of the critical areas in Organization for achieving the desired level of capability improvement.

6-4. Selecting the most appropriate alternative by *Compromise*

"Compromise is an effort to approach or emulate the ideal solution as close as possible" [**Zeleny**, 1982, p315].

Compromise solution is achieved by minimizing the composite distance of all goal values from their ideals.

If $X=\{x|g_r(x)\le b_r|r=1,2,\ldots m\}$ is the decision space, and $Y=f(x)=(f1,f2,\ldots fm)$ is a set of objective functions defined on X,

then, a generalized distance measure is expressed as:

$$d_p = [\sum_{i=1}^{l} \lambda_i^p (y_i * - y_i^k)^p]^{1/p} \qquad (6.14)$$

where $p \in [1,\infty]$, is the power parameter.

λ_i = weight of $(y_i * - y_i^k)$, $\lambda_i > 0$.

The choice of p influences the measure of distances. In fact, for $p=\infty$,

$$d_\infty = \max\{\lambda_i (y_i * - y_i^k)\} \qquad i=1,2\ldots l, \text{ number of criteria}$$
$$k=1,2\ldots m, \text{ number of alternatives}$$

ie., the largest deviation dominates the composite distance.

Any point y^{k*} is a compromise solution if it minimizes d_p in Eqn. 6.14 for some choice of weights $\lambda_i > 0$, $\Sigma\lambda_i = 1$, and $1 \le p \le \infty$. Each compromise solution satisfying these conditions is nondominated. For $1 \le p \le \infty$, the compromise solutions are also unique [**Zeleny**, 1982].

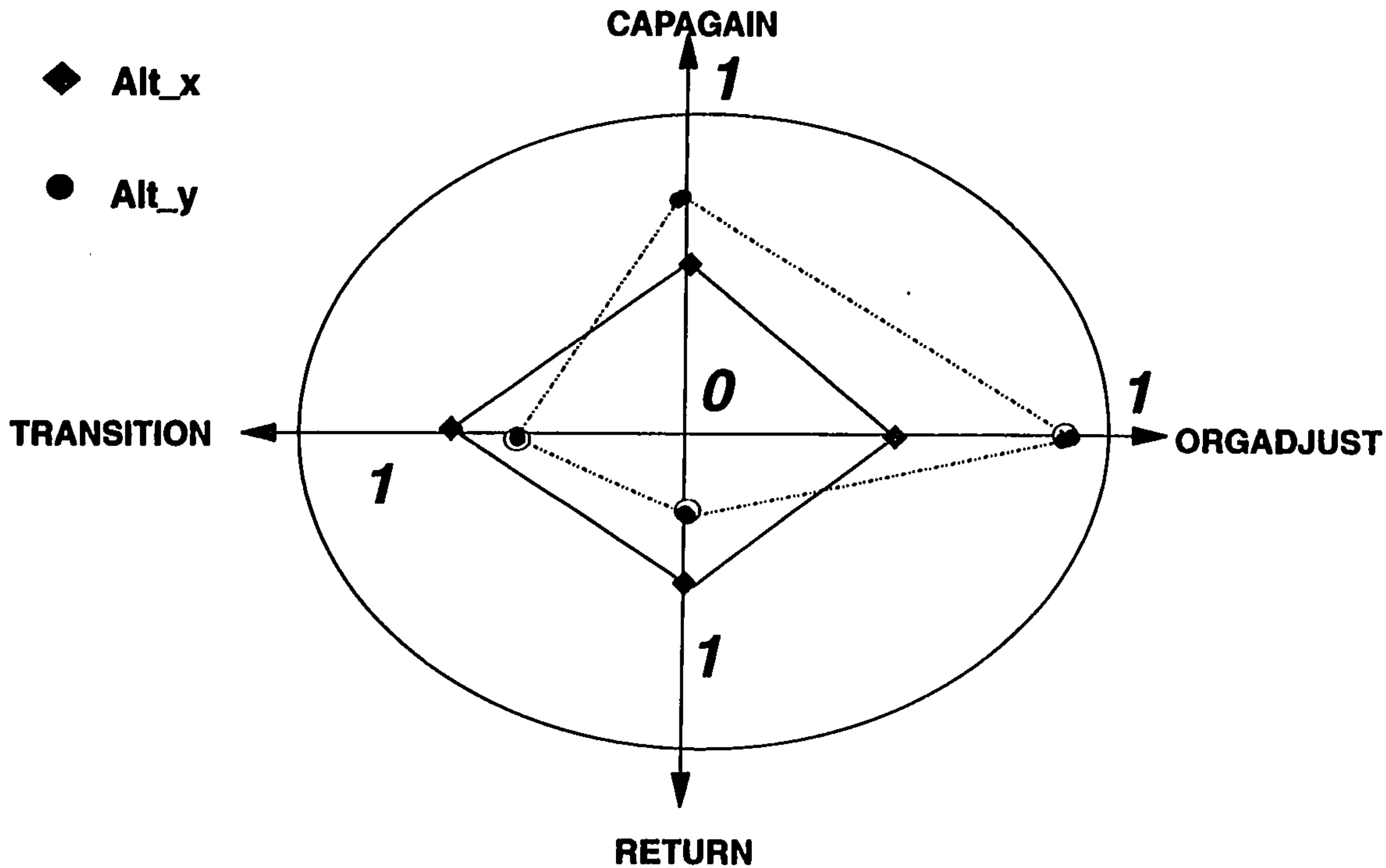


Fig. 6-2. Goal Space of Multiple Objective Formulation

Fig.6-2 illustrates the 4-Dimension goal spaces of the problem. Applying these concepts to the problem on hand, the Compromise Programming Goal can be defined as follows:

$$d_p = [\ \lambda_1^p (1 - CAPAGAIN\_r)^p$$
$$+ \lambda_2^p (MARR - IRR\_r)^p$$
$$+ \lambda_3^p (TRANSITION\_r - 0.1)^p$$
$$+ \lambda_4^p (ORGADJUST\_r - 0)^p\ ]^{1/p} \qquad (6.15)$$

The compromise solution is the Alt_r* that minimizes d_p under given conditions of $\lambda_i > 0$, $1 \le p \le \infty$.

6-5. Summary of the present modelling approach

The present model has the following major features:

1) Start with identifying performance capability improvement needs and evaluate the candidates of system configurations that are most likely to be implemented with success within the organizational constraints.

2) Incorporate qualitative judgement and quantitative performance data to evaluate system capabilities and justify acquisition of AMT.

3) Create an interaction between decision makers and the model, and use flexibility of decision makers to change the factors.

4) Formulate the issues within a multiple criteria decision making framework, and give simultaneous treatment of multiple

goals through compromise programming.

5) The status quo is not considered as an alternative in the model formulation. Therefore upgrading of manufacturing capability is enforced.

6) Indications to organizational changes are also generated as an output.

7) The real challenge arises in establishing measurement and obtaining data for each coefficient in the equations, especially for Goal1. For Goal2 and 3, works by **Son** [1991b], **Stam&Kuula** [1991], and **Kennedy** [1993] may be of help. The validity and feasibility of the methodology in real life situations is tested through a case study, to be presented in the next chapter.

Chapter 7.

Model Illustration and Validation by a Case Study

A case study has been conducted, with the co-operation of local firms, with two goals in mind: to test the validity of, and to illustrate the working procedure of, the proposed methodology. Data are obtained from management interviews, field observations and industrial sources. The case scenario is presented below with all names of the participants camouflaged. The company is denoted as WAP plant for the purpose of this illustration.

7-1. Case analysis by Task Modules

Analyses are organized according to the conceptual model of Fig.3-1 in Chapter 3. The Task Modules of Fig.3-1 are listed below for ease of reference:

Module 1: Strategic objectives and capability requirements.
Module 2: Activity chain and performance capability measures.
Module 3: System performance targets and capability gaps.
Module 4: Current technological system profile and bottleneck.
Module 5: Technological upgrading program alternatives.
Module 6: Evaluation criteria.
Module 7: Decision criteria and procedure.
Module 8: Recommendation of the best alternative.
Fig.7-1 gives a schematic view of the Task Modules.

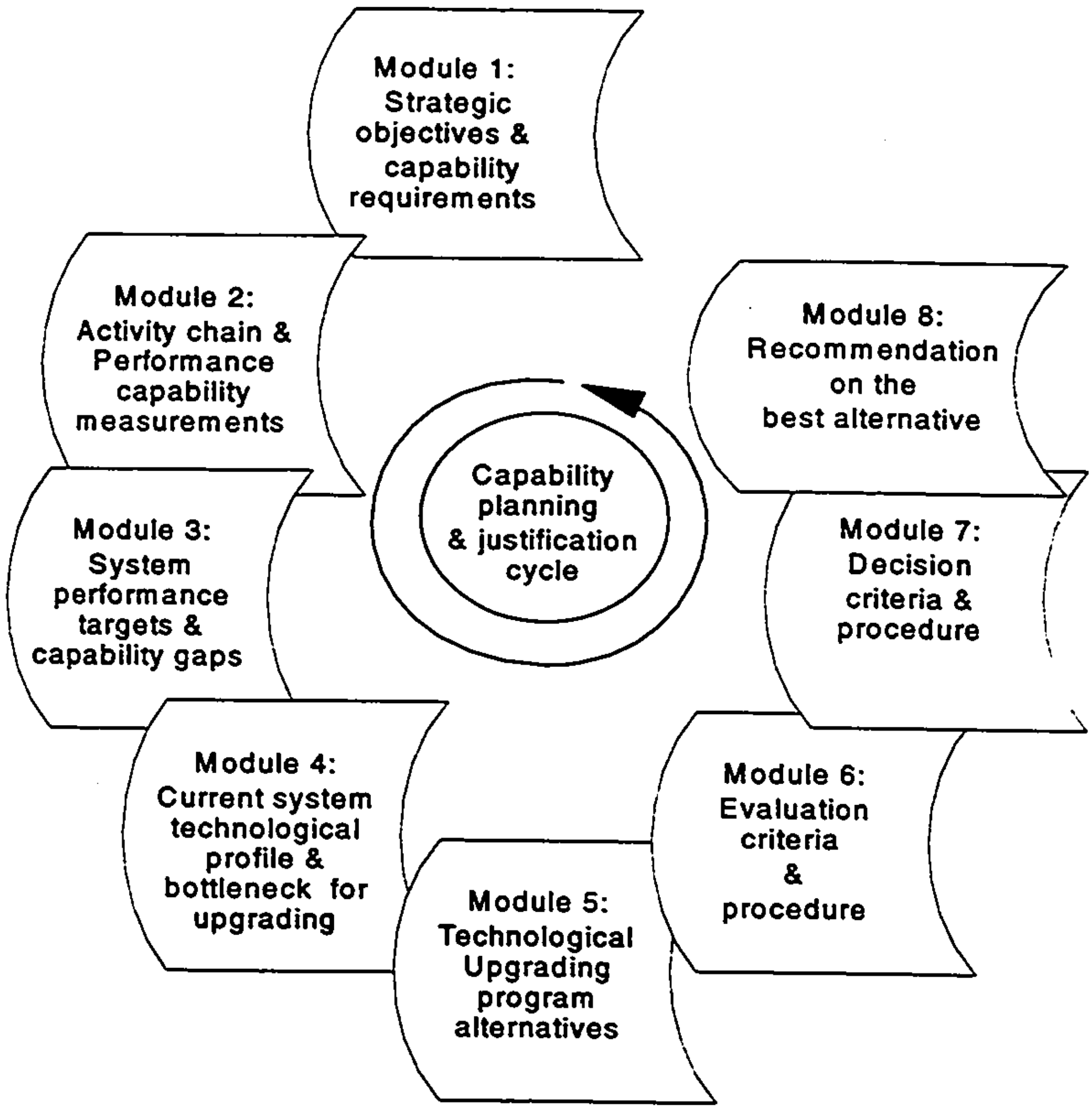


Fig.7-1. Task modules essential for applying the methodology to real cases

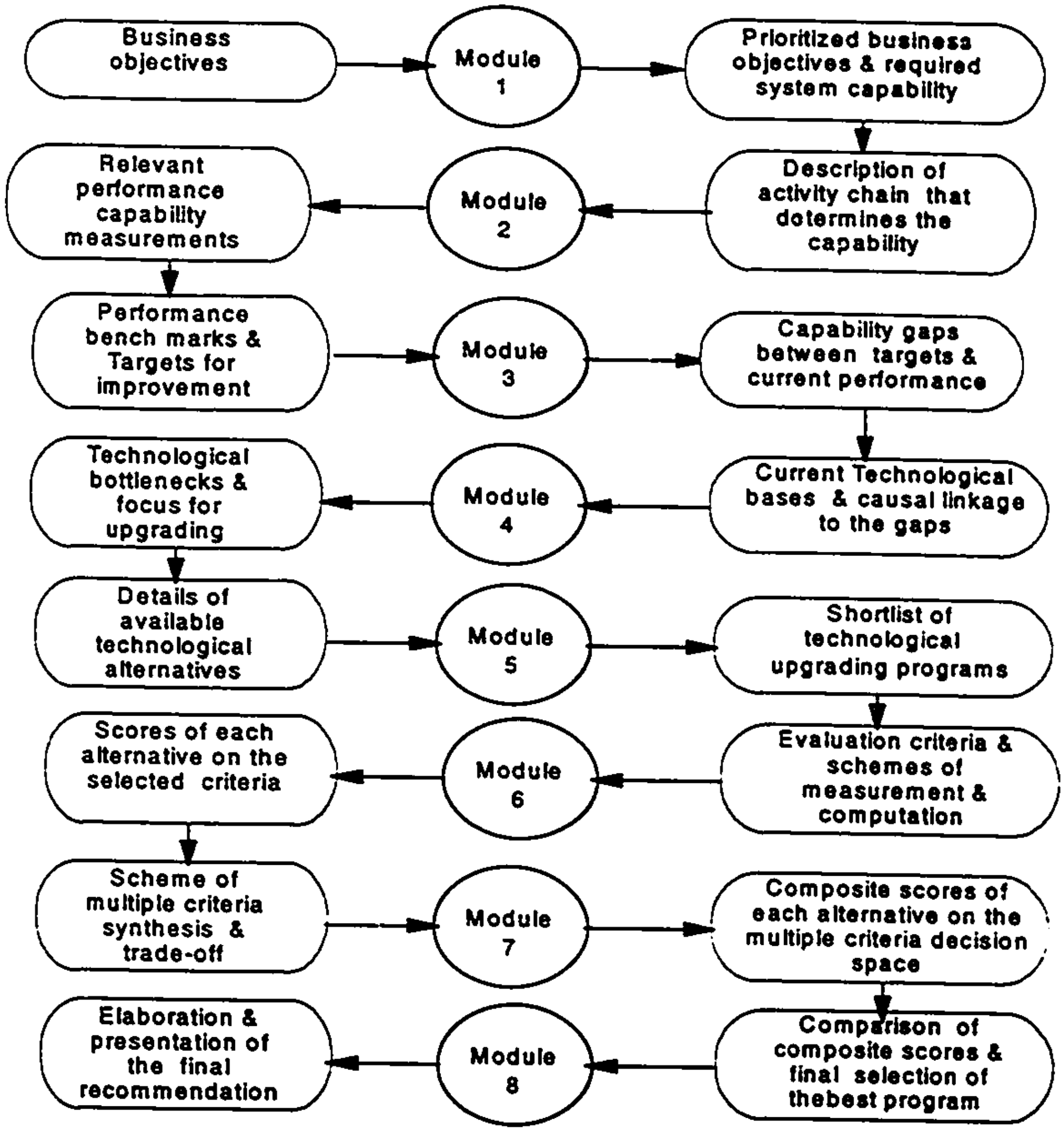
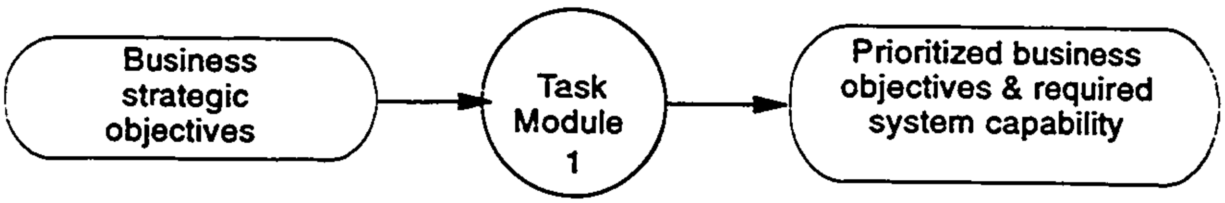


Fig.7-2. Information input & output requirement by task modules



Identify Strategic Objectives & Capability Requirements

What to do:

Analysis and Understanding:

-Business environment
-Strategic direction of the entity under study
-Management objectives and priorities
-Capability requirements

How to do:

- Managerial interview & survey
- Industrial background research

Format of data:

-Descriptive and qualitative

Tools of aid:

- Questionnaires
- Multiple attribute weighing scheme (AHP package)

Fig. 7-3. Guide of Task module 1

The required data inputs and outputs of the task modules are detailed in Fig.7-2 as an operating guide for would-be users. A copy of the questionnaire and detailed data treatment are attached in the Appendices.The module analysis outcomes are presented below.

Task Module 1: Scenario and Perspective - JIT at WAP plant

Task Module 1 is detailed in the Fig. 7-3. Its data input and outcome is presented below. Pressed by fierce competition, American auto makers had to streamline their production process in order to improve productivity and quality. Just-In-Time (JIT) manufacturing is one of the philosophies being adopted for the purposes. JIT manufacturing eliminates excess work-in-progress (WIP) inventory by organizing the production flows according to the down-stream demand pull. The successful implementation of JIT (denoted as the strategic objective G1) is dependent on the capability of production logistic systems to deliver the right quantity of required parts and components to the right place, at right time. At WAP Plant, the supply of components from external suppliers is coupled with the WAP plant operation with a staging strategy to ensure a JIT mode. The WAP profile is summarized in Tables 7-1 and 7-2.

Table 7-1. Profile of the production operations at WAP plant

Industry	Car assembly
Product lines:	Luxury car series, mix of two models
# Variants per model	60
Production volume range	5000-10000 units per month
Production pattern	90% made to order, 10% made to stock
New product introduction rate	two per year
Number of major customers	1500 (dealerships & fleet sales)
Number of major suppliers	20
No. Production facility site	single location
Number of shifts per day	2

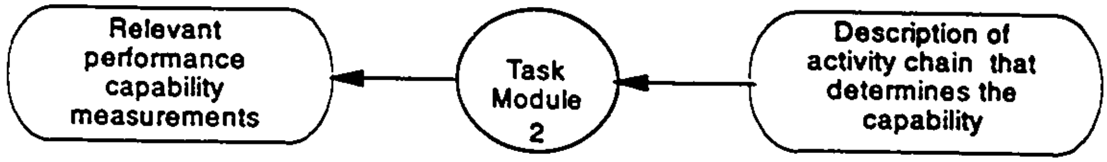
Table 7-2. Logistics operation features in the WAP Plant

Production logistics mode	JIT, mixed models
Supplier buffer in the plant	Stage yard, 5 trailers average
Receiving flow	Supplier->stage yard->dock->line
Number of docks/receiving point	2
Type of delivery transportation	Rear-loading Trailers
Type of cargo received	Semi-finished parts (side panel)
Cargo conditions	Dedicated racks or pallets
Average throughput rate per dock	60 trailers per week (5 days)
Dock throughput capacity	60 trailers per week
Trailer load/unload methods	Fork lift trucks (1 per dock)

Task Module 2: Identify activities and performance measures

Fig.7-4 gives the task definition. Notations of Chapter 5 (Table 5.1) will be applied in the following texts.

A receiving dock is a potential bottleneck in the material flow pipeline, the interface between supplier and the plant. Material flows through a receiving dock at WAP are illustrated in Fig.7-5. Trailers of components from the suppliers are



Analysize Activity chain & establish Performance measurements

What to do:
-Detailed description of the activity chain in the current operating system that determines the capability

How to do:
-Interview with line operators
-Field observations
-Engineering analysis methods
-Survey of historical records / existing standards / bench marks

Tools of aid:
- Industrial manuals / standards
- Multiple attribute weighing scheme (AHP package)

Data format:
-Descriptive,
-Statistical

Linkage:
- Module 1, Module 3, Module 5

Fig. 7-4. Guide for Task Module 2

delivered by a third party contractor fleet to a staging yard 400 meters away from the receiving docks in the plant; on average 5 trailers of parts are staged at the yard at one time. Major activities around the receiving dock are illustrated in Fig.7-6. These activities include (using notations from Fig.5.1):

FA1: A switcher tractor of the WAP plant brings full trailers to docks, and returns trailers of empty racks back to the yard;

FA2: The parts (packed in racks) in the trailer at the dock are unloaded onto the stacking area beside the docks;

FA3: Parts are transferred from the stacking area to an intermediate buffer (eg., Over/Under system) to be merged into the assembly line as required;

FA4: Empty racks are transferred back to the dock; and

FA5: Racks are reloaded onto the trailer waiting at the dock.

The current trailer loading/unloading method at the docks is by operators driving forklift trucks (High-Lows) into and out of the trailers. Supporting JIT production (G1) is the paramount objective of dock operations, for which Reliability and Efficiency are the basic performance criteria. Loading and unloading goods from trailers by a fork lift truck (FA2 & FA5) are, however, potentially risky activities. Many factors impose danger to the fork truck driver who must drive through the restricted spaces inside the trailers, over the dock floor

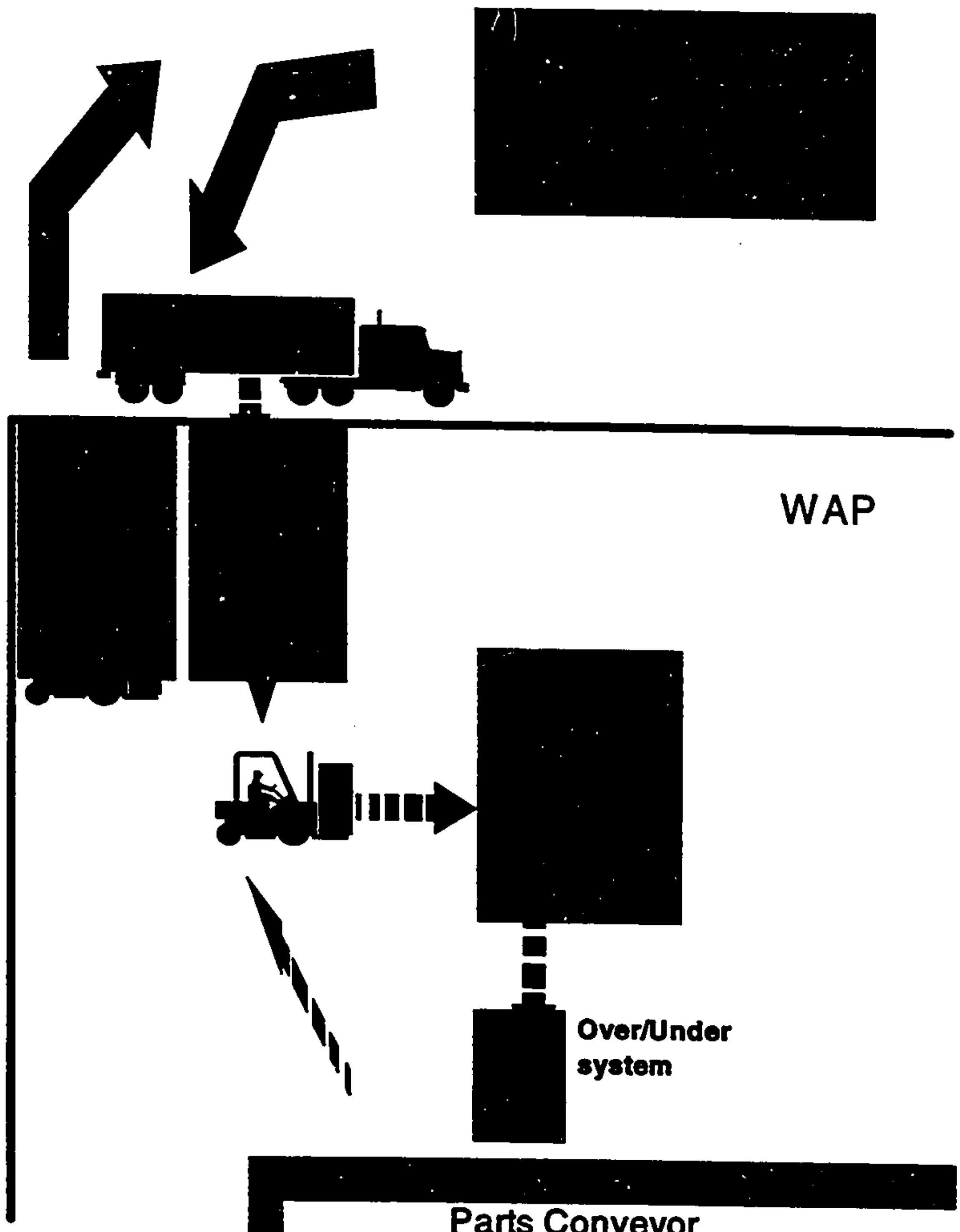


Fig.7-5. Material flow through receiving docks

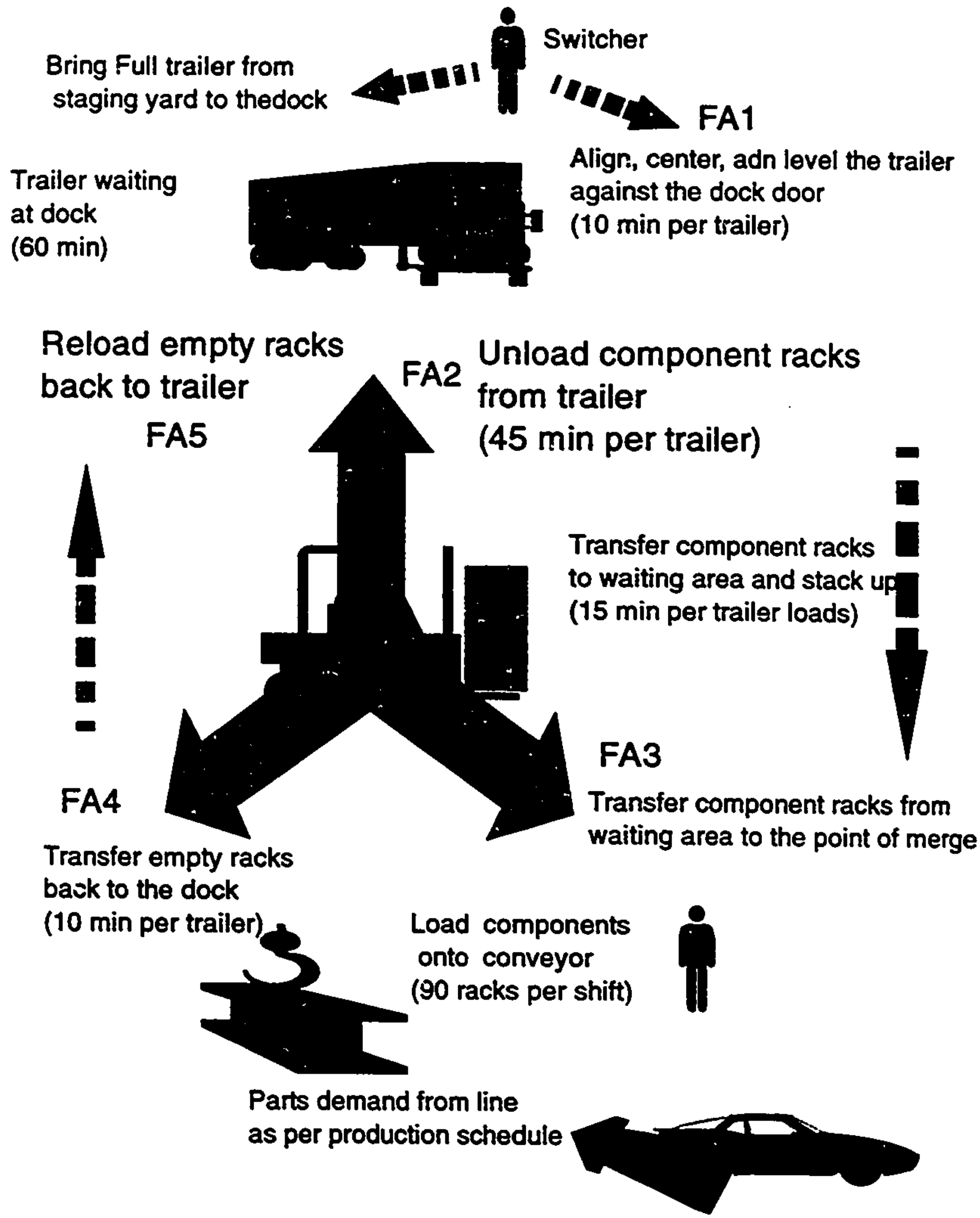


Fig. 7-6 Activities arround loading/unloading at receiving docks

leveller, and on the dock floor with heavy loads, insufficient lighting and perhaps blocked view. Skills and concentration of operators are critical. Operator safety at the workplace is a moral and legal mandate (eg., OSHA Regulations), hence the number one constraint during the dock operations. A set of capability requirements {OOj|j=1,2,..5} to dock operations is identified and prioritized by management, as shown in the Table 7-3.

Table 7-3. Prioritized capability objectives for dock operations

JIT Unloading (G1)	OO1	OO2	OO3	OO4	OO5	Priority (WOO)
OO1) Efficiency	1	1/7	1/5	5	7	.101
OO2) Safety		1	9	9	9	.634
OO3) Reliability			1	7	7	.205
OO4) Flexibility				1	1	.031
OO5) Low costs					1	.030

(CR = .20)

Sub-objectives {PAjh|j=1,2,..5, h=1,2,..h(j)} under each performance capability measure {OOj} are also identified by the management, as displayed in the Fig. 7-7.

Current performance of the receiving docks at WAP has been a source of concern, and improvement is imperative. Further analysis, to be described step by step below, aims to derive a recommendation to WAP plant management of the appropriate dock improvement program.

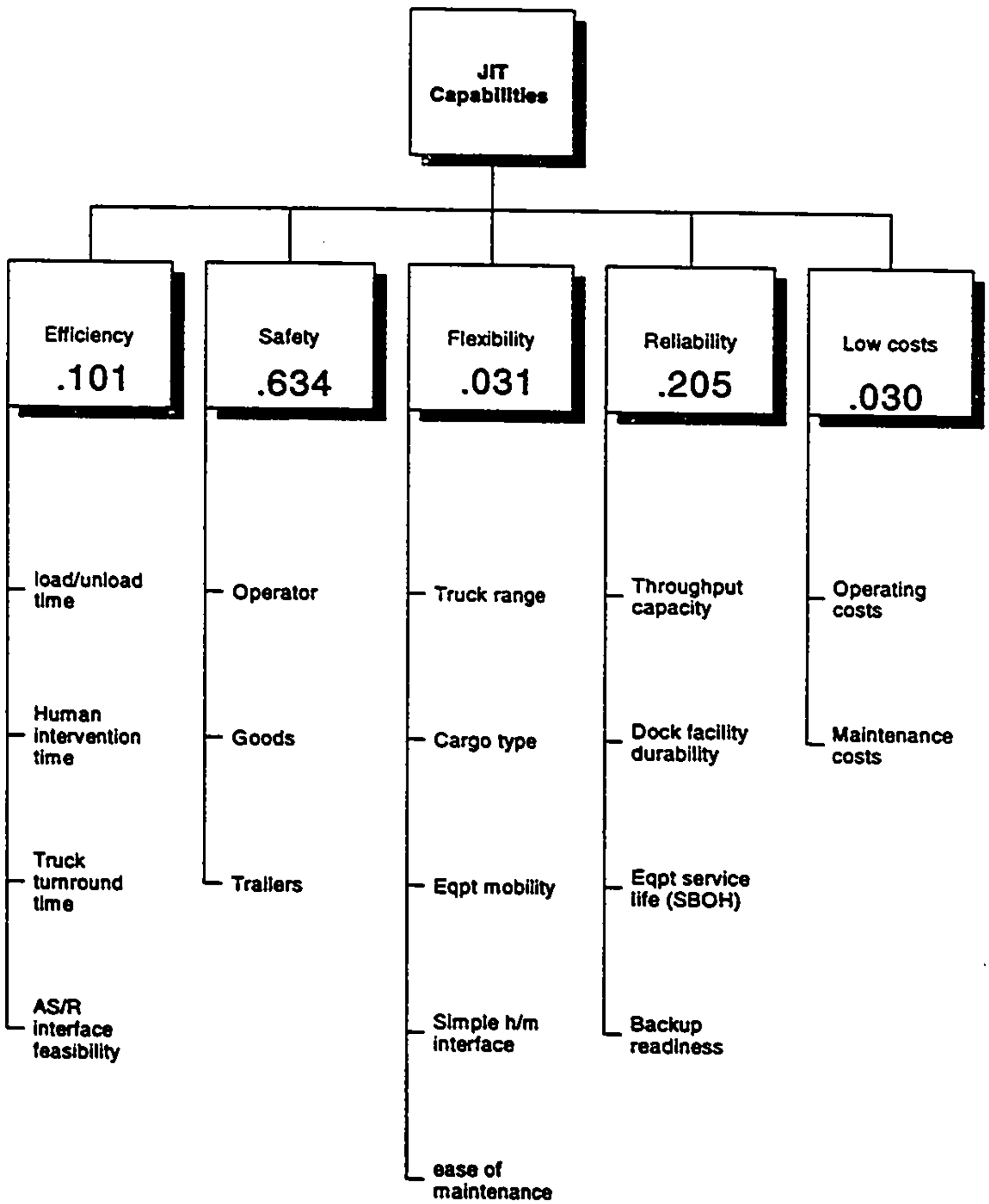
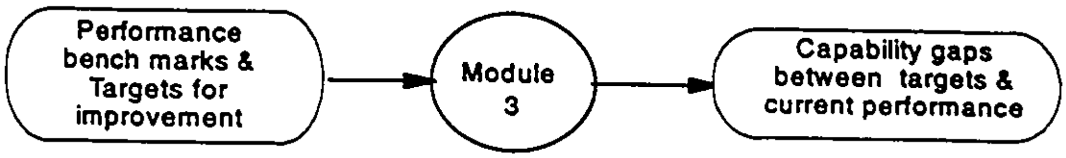


Fig.7-7. Objectives and Performance Measures
-- an output of Task Module 2



Establish pe.fromance targets and Identify current system capability gaps

What to do:

a) Prioritize sub-attributes of each performance objectives;
b) Setting quantified performance targets for each measures with reference to bench marks and strategic objectives;
c) Compare current system performance with the targets to identify system capability gaps.

How to do:

a) Prioritizing sub-measures
-Ask management to assign priority weights to each sub-measure of performance objectives;
-Calculate composite weights of each sub-measure using eigen-vector method (AHP package);

b) Setting targets
- Survey customer requirements /bench marks / standards
- State levels of performance required by the strategic objectives
- Assign subjective values to measures that do not have quantitative data

c) Identifying gaps
- Take the difference between current level and target level of a measure.

Tools of aid:

- AHP package
- Competitive intelligence techniques

Fig. 7-8. Guide for Task Module 3

Task Module 3: Set performance targets & Identify current system capability gaps

Fig.7-8 gives the definition of Task Module 3. The performance capability targets in each category of Fig.7-7 are established by management and listed in the Table 7-4. A subjective scale of 1 to 5 is used to distinguish levels of certain measures (indicated with '*') for which objective data are not readily available. The scale is defined as follows (interpreted in accordance with individual measures):

1=low, 2=lower medium, 3=medium, 4=higher medium, 5=high

Comparison between the levels of current performances and the targets reveal the capability gaps in the current system.

Table 7-4. Performance Measures and Identification of Gaps

Performance Measures (pa_{jh})	Weight (wpa_{jh})	As-is (M_0)	Target (M_u)	Gaps (M_u-M_0)
unload time/truck (min)	.046	45[1]	5	-40
human intervention/load (min)	.007	75[2]	15+10[3]	-50
truck turnround time (min)	.043	75[4]	35[5]	-40
AS/RS interface possibility*	.005	1	5[6]	4
dangers of operator injury*	.508	5[7]	1	-4
dangers of goods damage*	.090	4	1	-3
dangers of trailer damage*	.036	5[8]	1	-4
throughput capacity(truck/h)	.120	.8[9]	6[10]	5.2
dock facility durability*	.023	4[11]	5	1
equipment life SBOH (hour)	.014	10k[12]	22k[13]	12k
backup readiness (1-5)*	.048	3[14]	5	2
truck range handling (1-5)*	.002	5[15]	5	n/c

Table 7-4. Performance Measures and Identification of Gaps

Performance Measures (pa_{jh})	Weight (wpa_{jh})	As-is (M_0)	Target (M_u)	Gaps (M_u-M_0)
cargo type handling (1-5)*	.002	3[16]	5	2
equipment mobility (1-5)*	.002	5	5	n/c
simple h/m interface (step)	.013	3[17]	1 [18]	-2
ease of maintenance (1-5)*	.011	2[19]	5	3
operating costs ($1000/yr)	.005	60[20]	30[21]	-30
maintenance costs ($k/yr)	.035	10[22]	2	-8

Notes:

(1) Unloading a 53ft trailer packed with 16 racks of body side panels.

(2) Human operation takes place in full 45 min of unloading and 25 min reloading when a fork truck is used.

(3) Time needed to transfer full racks from the dock to the assembly line, and transfer empty racks back to the dock, using a fork truck.

(4) Time between a trailer's arrival at and departure from the dock, including unloading, reloading, and waiting time.

(5) Including unloading/reloading and waiting time at the dock.

(6) Automated loading/unloading docks can be coupled with gantry robot and conveyor systems to form fully automated links to the line.

(7) Associated with fork truck operation.

(8) Associated with fork truck operation.

(9) Throughput = (60min/h)/{load&unload_time(75min)/trailer}.

(10) Throughput = 60min/{load&unload_time (10min) per trailer}

(11) Including the door, leveller, lock, seals.

(12) SBOH = service hours before overhaul, measured by engine hours.

(13) The best available fork trucks.

(14) Adjacent docks or other fork trucks used as back up.

(15) Dedicated trailers are used.

(16) Dedicated racks are in use.

(17) 3 steps needed for preparing unloading with a fork truck, including:

(i) set dock-lock, (ii) open dock door,(iii) raise dock leveller.

(18) Pressing one single button to trigger the series of activities of automated dock devices.

(19) Associated with maintaining fork truck and dock devices.

(20) Costs accrued by employing one forklift truck and one driver on each dock, ie., a pair of fork trucks for a pair of adjacent docks.

(21) Halving the costs by sharing a fork truck on a pair of docks.

(22) Costs accrued by maintaining dock equipments other than fork trucks.

A graphical illustration of the gaps in key capability areas is shown in the Fig 7-9. As the example, the implication of the gap in unloading speed on the safety stock level is shown in the Fig.7-10 and Fig.7-11. With the current unloading speed at 45 minutes per trailer, the WAP plant has to set the safety stock at a level equivalent to about two trailer loads (32 racks) at the current consumption rate, with the lowest on-hand (ie., excluding those being unloaded at the receiving dock) stock point at 23 racks of parts, enough to feed the assembly line for about 115 minutes. If the safety stock level were set at one trailer load (16 racks), the lowest on-hand stock point could be as low as 7 racks, lasting for only 35 minutes before the line would be shut down due to stock out, were there any delay in deliveries. In contrast, at the targeted unloading speed of 5 minutes per trailer, the same safety stock level of 16 racks would have the lowest on-hand stock point at 15, which at current production rate were able to sustain the assembly line for 75 minutes, which is the

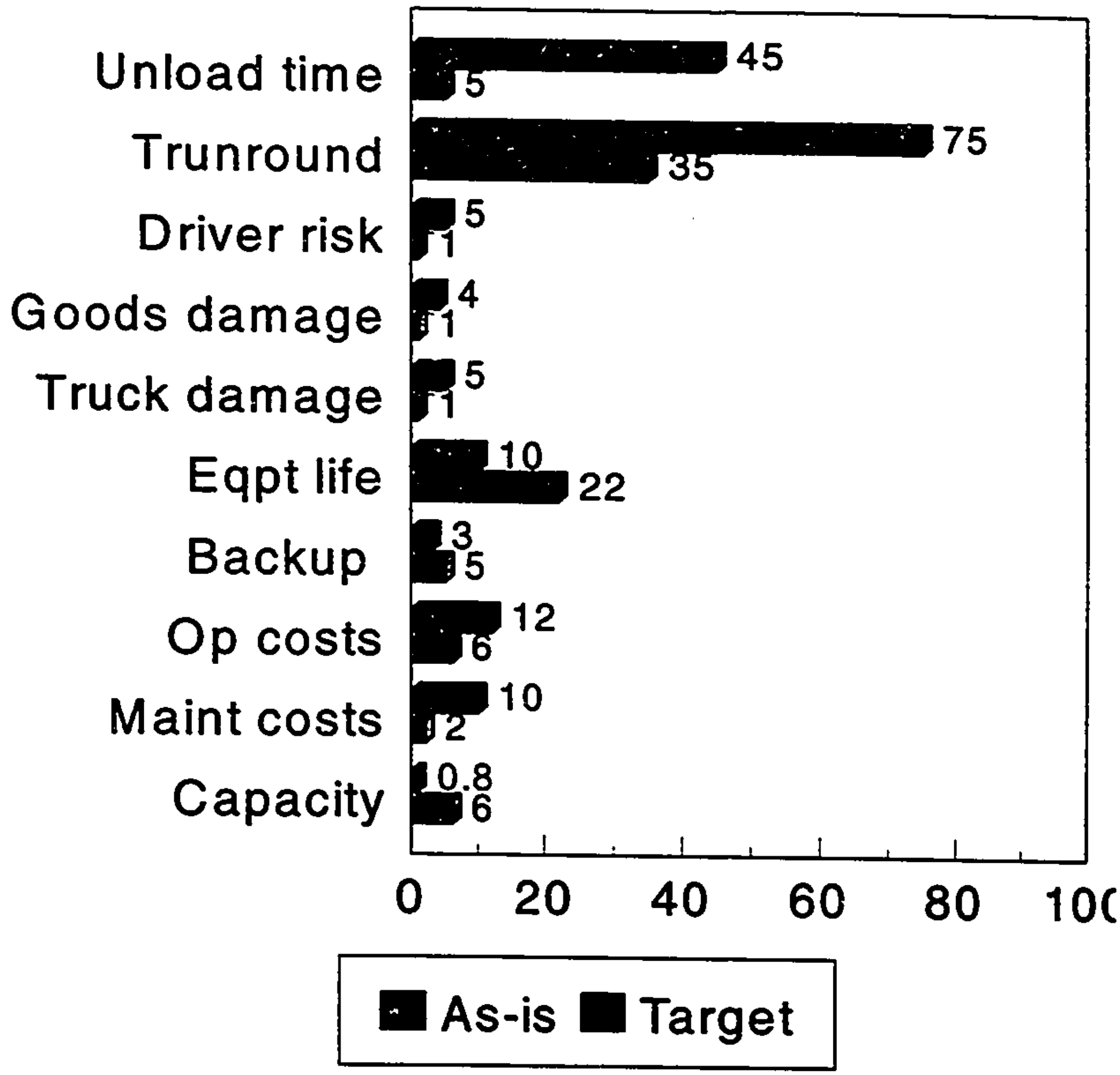
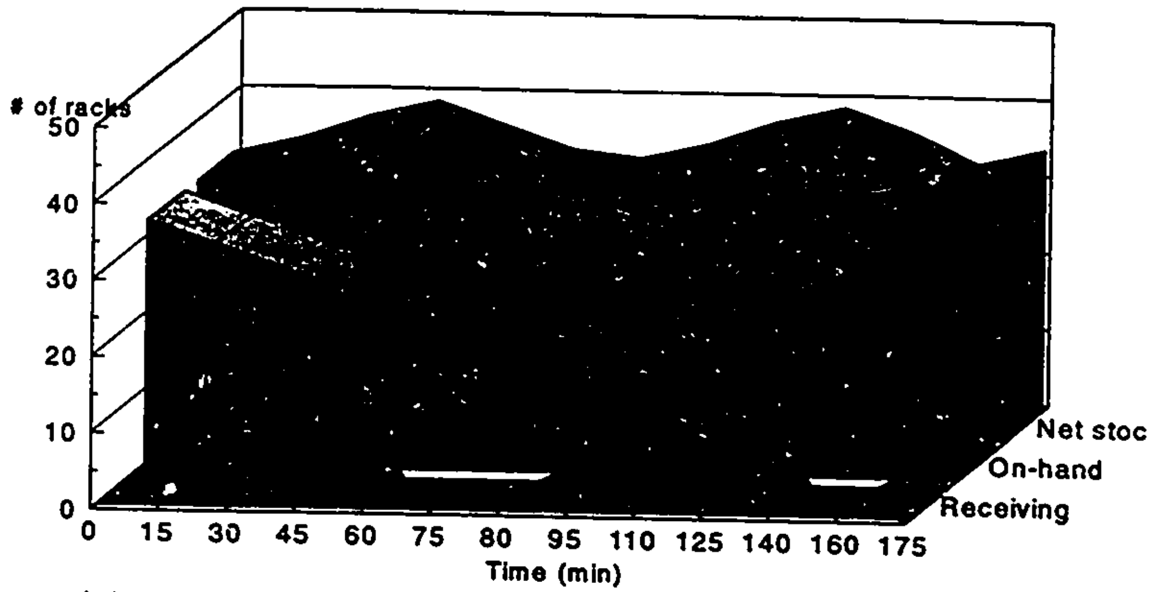
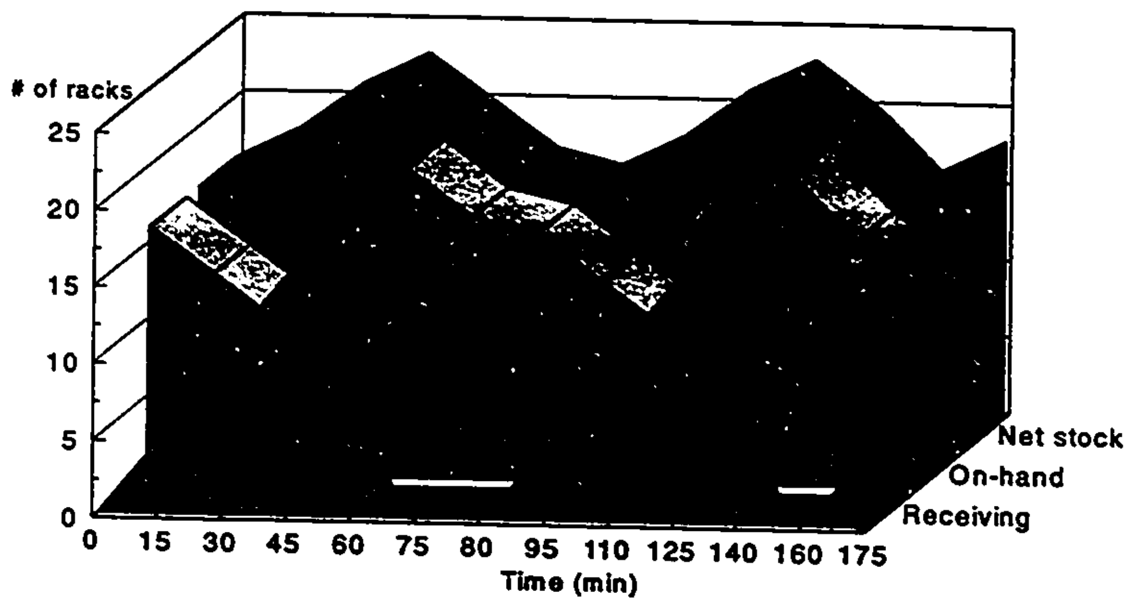


Fig.7-9. Identification of major performance gaps
- an output of Task Module 3

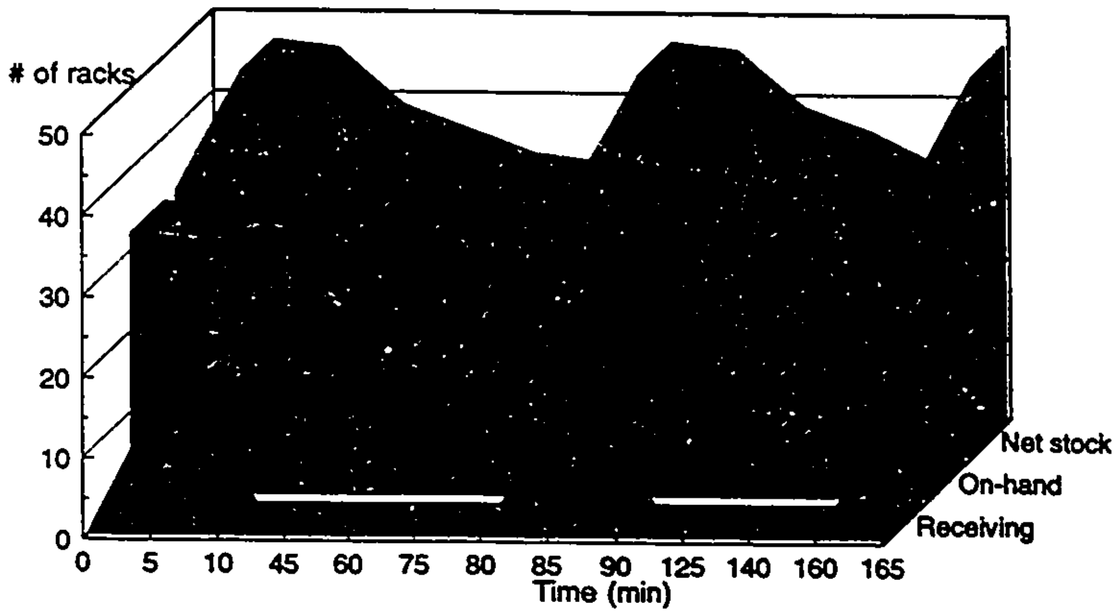


a) Lowest on-hand stock = 23 racks when buffer size is set at 32 racks (two trailer loads)

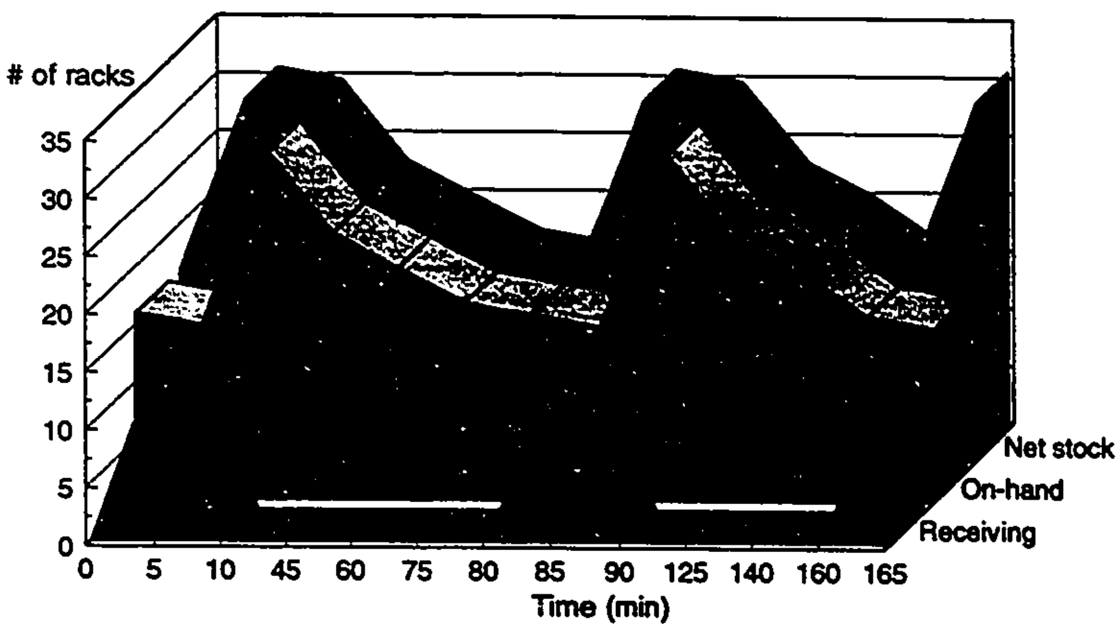


b) Lowest on-hand stock level = 7 racks when buffer size is set at 16 racks (one trailer load)

Fig. 7-10 . Safety stock levels at current unloading speed



a) Lowest on-hand stock = 31 racks when
buffer size is set at 32 racks (two trailer loads)



a) Lowest on-hand stock = 15 racks when
buffer size is set at 16 racks (one trailer load)

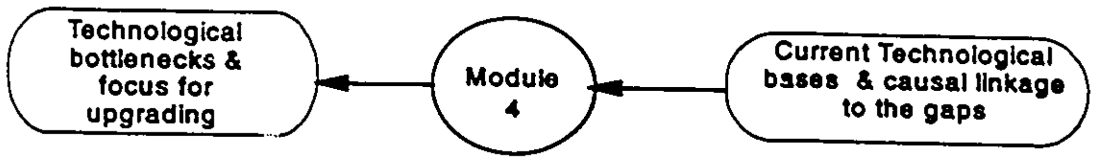
Fig. 7-11 . Safety stock levels at targeted unloading speed current truck turnround time.

Task Module 4: Identify technological bottlenecks

Task definition is given in Fig.7-12. Material Handling, (denoted by TE22 in the Chapter 4), is the main technological category relevant to the loading/unloading operations at a receiving dock. In the present case context, the technological base **TE** can be divided into the following subareas:

Table 7.5. Current receiving dock technological base profile

Categories	Dock devices **TE1**	Loading/ Unloading tools **TE2**	Dock-side Transferring devices **TE3**	Storage & Retrieval facility **TE4**
Current base & Activities supported	Automated Locks, Levellers, Door & Seal **FA1**	Fork lift trucks **FA2 & FA5**	Fork lift trucks **FA3 & FA4**	Automated Over/Under system **FA3 & FA4**
Feature & capacity	Standard	Battery powered, general purpose	Battery powered, general purpose	Custom design, Holds & move 16 racks



Assess current technological base supporting the activity chain &
identify bottleneck area for upgrading

What to do:

a) Assess the technological base and identify links between technology item and performance gaps;

b) Identify the critical technology currently in use that limit the key system capability.

How to do:

Engineering analysis and / or qualitative judgements on the possible causal-effect relations between the identified performance gaps and the technology items in use.

Tools of aid:

- Subjective rating scheme (eg. scales of 1 to 5)
- QFD technique and package
- Fish bone chart
- AHP method and package

Data format:

- Descriptive

Fig. 7-12. Guide for Task Module 4

The technological areas in the dock operations can be assessed by several methods to identifying the critical areas to which the major performance gaps may be attributed. Engineering analysis, QFD techniques, Fishbone charts, and the eigenvector method described in the Chapter 5 are all feasible for the purpose. In the present case study the eigenvector method is used. The upgrading priorities of the technological subareas are summarized in the Table 7-6.

Table 7-6. Dock technological base upgrading priorities

	Speed .101	Safety .634	Reliability .205	Flexibility .031	Costs .030	Priority WTE
TE1	.055	.213	.102	.056	.049	.165
TE2	.669	.623	.662	.646	.556	.635
TE3	.220	.123	.171	.244	.259	.151
TE4	.055	.041	.065	.054	.136	.051
CR =	.049	.107	.092	.092	.089	

The current unloading/loading method by fork lift trucks (TE2) is identified as the priority area for improvement. This can be underscored by the observations that TE2 may be the major root causes for the docks' capability gaps, in particular:

1) The permeance of the dangers of operator injury and goods/truck damage inherent in the forklift truck operations. An industrial accident costing a human life was recently reported in a similar environment.

2) The long time needed for unloading/reloading a trailer, and consequently the low trailer utilization rate; currently a fleet of 10 trailers is required to supply the parts.

3) The long unloading/reloading time restrict the current dock

capacity to about 6.4 trailers per shift (12 trailers per dock per day). With current parts (side panels) consumption rate at about 6 trailer loads (96 racks) per day, the docks are operating at almost 100% capacity, imposing a potential constraint if the demand rate is to be increased, as well as a danger of stock out to the assembly line if a dock jams. (Refer back to Fig.7-10).

Task Module 5: Identify capability improvement alternatives

The strategic planning task for the dock operations management is to come up with a solution that brings the dock operations in line with the JIT production objectives of the plant, by balancing the concerns of capacity and efficiency with safety and costs. One proposition to add six more conventional type docks has been made to address the capacity constraint. Meanwhile, new technologies, such as new conveying devices, are being developed that enable the reduction of loading or unloading time to 3-5 minutes by handling the entire truckload as a "slug" at once, therefore increasing dock throughput capacity. Automated loading/unloading technology also promises reduction of risks of operator injury and goods damages associated with fork trucks. Possible improvement programs are identified through a vendor survey. Three options are listed in Tables 7-7 and 7-8 below.

Table 7-7. Outlines of alternative dock improvement programs

Alt_r X_{k0r}	Main features	Program focus	Conditions
Alt_1 X_{101}=1 X_{201}=1 X_{301}=0 X_{401}=0	6 new docks of current type, with manual loading/unloading by fork trucks	Capacity, Reliability Upgrading TB2 possible (new fork trucks)	Space availability, Training fork truck drivers to OSHA standards
Alt_2 X_{102}=0 X_{202}=1 X_{302}=0 X_{402}=0	Automated Dock-Mounted-Loader/unloader (ADML), eg., the shuttleDOCK™, on an existing dock, interfaced with line by a forktruck that also serve the adjacent dock	Safety, Speed, Reliability, Capacity Changing TB2	Goods packed on slipsheets or racks
Alt_3 X_{103}=0 X_{203}=1 X_{303}=0 X_{403}=0	ADML + Vehicle-Mounted Roller-Tracks (VMRT), eg, Roller-Track&Slip-chain systems, on an existing dock, interface with line by forktrucks.	Safety, Speed, Reliability, Capacity Changing TB2	Modification to truck/trailers, Palletized goods

Task Module 6: Establish measures and Evaluate alternatives

(See Fig.7-13 for task module definition). Evaluation criteria is case dependent. In the WAP plant case, the influencing factors (Technological, Organizational and Resource Factors) identified in Chapter 4 are verified by the management respondents. Accordingly, a set of evaluation criteria is selected to include the four dimensions: **Capability Gains, Investment Returns (ROI), Project Transition Time, and Organizational Incompatibility.** The eigenvector method has been used to obtain the priority weights of the four criteria. The four dimensions and their sub-attributes are shown in the Fig.7-14.

Sub-Module 6-1: Capability Gains by Alternatives

Sub-Task 6-1-1: Estimate performance levels of alternatives: Expected performance capability improvements by each alternative are projected in the Table 7-8. The performance data are based on one dock, either with ADML (Alt_2 and Alt_3) or without (As-is and Alt_1).

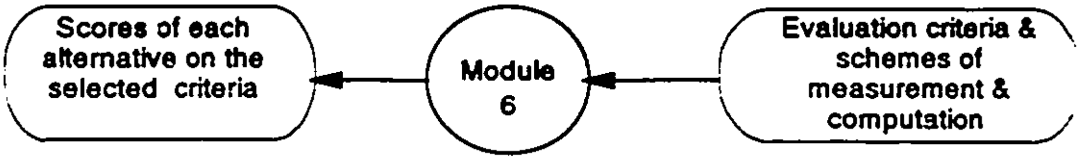
Table 7-8. Projected Performance Levels by Alternatives

Performance Measures	Target M_u	As-is M_0	Alt_1 M_1	Alt_2 M_2	Alt_3 M_3
unload time/trailer (min)	5	45	45	5	3
trailer turnround time(min)	35	75	75	35	35
dangers of operator injury	1	5	5 [1]	1	1
dangers of goods damages	1	4	4	1	1
dangers of trailer damage	1	5	5	2 [2]	2 [3]
throughput capacity (trailers/hour)	6	.8	4.8 [4]	6 [5]	10 [6]
dock facility durability [7]	5	4	4	5	5
equipment life SBOH (khr)	22 [8]	10	22	20 [9]	16 [10]
back-up readiness (1-5)	5	4	4	4 [11]	1 [12]
cargo type handling (1-5)	5	3	3	4	4
simple h/m interface (step)	1	3	3	1 [13]	1 [14]
ease of service (1-5)	5	2	2	4	3
operating costs ($000/year)	30 [15]	60	60 [16]	30 [17]	30 [17]
forktruck maintenance($k/y)	1.2 [18]	2.4	2.4 [19]	1.2 [20]	1.2
dock maintenance ($000/yr)	2	10	10 [21]	2 [22]	8 [23]

(Notes:

(1) Rigorous fork truck operator training procedures (OSHA) must be followed, which may reduce the risk.

(2) Racks may occasionally hit a truck when reloading due to tight



Establish criteria and procedure for alternative evaluation
Evaluate each alternative by selected criteria

What to do:
-Adapt the performance measures established in the Task Module 2 as the basic measurement;
-Establish additional evaluation criteria as appropriate;
-Obtain data or estimations of alternative candidate performances in each selected dimension of measurement;
-Calculate the commeasurable (unitless) scores of each candidate on the selected criteria.

How to do:
-Obtain management confirmation of selected evaluation measures;
-Study the specifications and investigate data of comparable performance of candidates on the selected measurements;
-Convert absolute performance measures into unitless scores by taking the ratio between the degree of improvement from as-is to candidate level and the performance gap in the measurement identified in the Task Module 3;
-Apply priority weights of performance measures obtained in Task Module 3 to the unitless scores of candidates in each measure to arrive at the composite scores for comparison.

Data format:
-Quantitative design specifications and performance data;
-Estimated performance data in the study environment;
-Established priority weights of measures.

Tools of aid:
-Vendor quotation and information package;
-Industry bench marks;

Fig. 7-13. Guide for Task Module 6

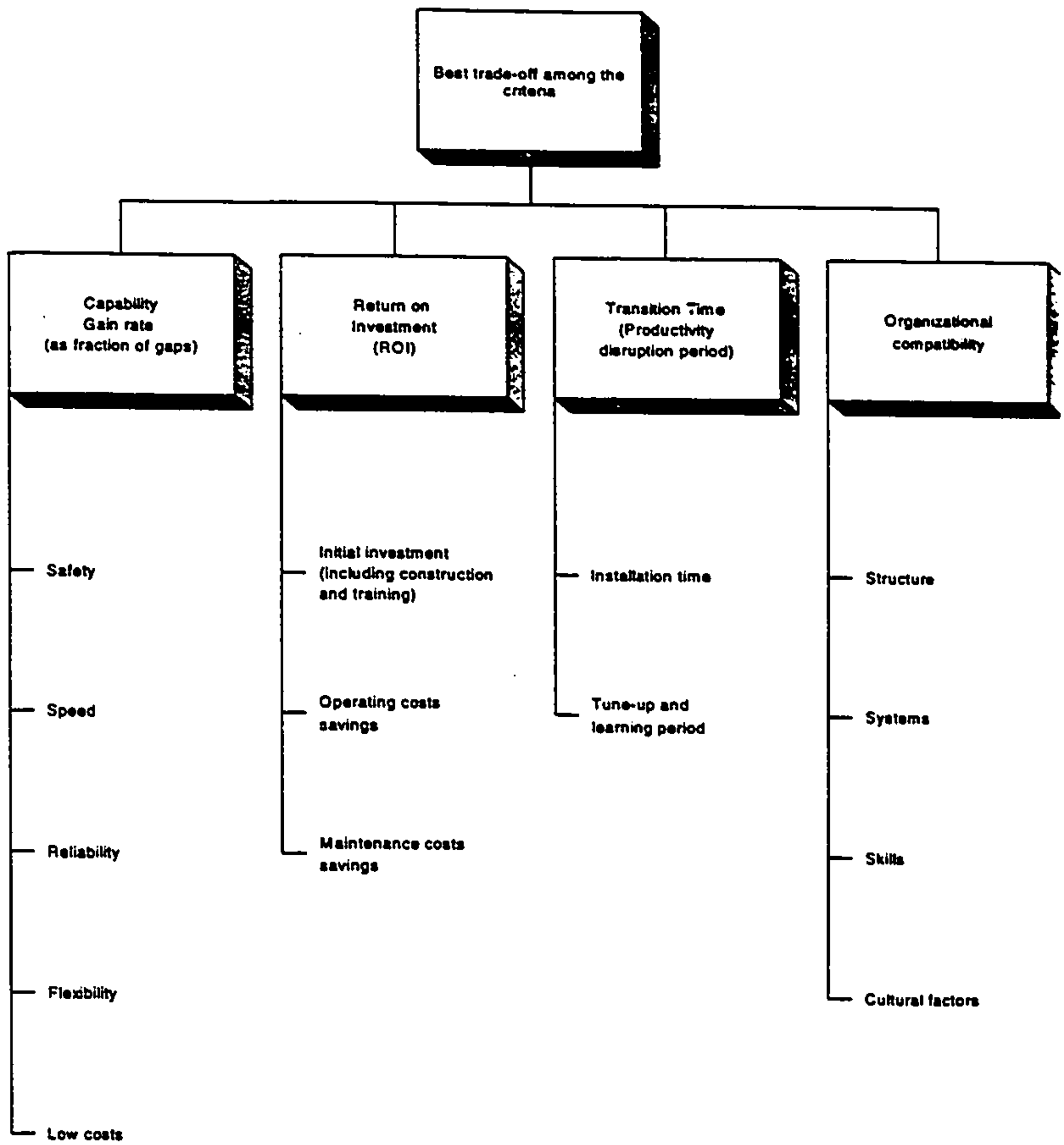


Fig 7-14. Evaluation criteria for WAP plant case

tolerance between racks and the trailer.

(3) Need dedicated trucks for the vehicle-mounted-roller-tracks.

(4) Total throughput capacity of 6 additional docks @ 0.8 each.

(5) Throughput capacity of shuttleDOCK when waiting time for empty racks is excluded.

(6) Throughput capacity of AHS system when excluding waiting time.

(7) Assume the same type of equipment (lock, leveller, door, etc) will be used for the new docks.

(8) Best available engine hours of fork trucks. (source: Modern Material Engineering, June 94)

(9) Estimated SBOH for shuttleDOCK, corresponding to 5 year services.

(10) Estimated SBOH for roller-track and slip chain systems.

(11) The shuttleDOCK relies on the adjacent dock for backup.

(12) The VMRT denies the access of forktruck to the trailers.

(13)&(14) One pushbutton control to operate the equipment.

(15) Halving the costs of using fork trucks.

(16) Employ one fork truck per dock, as of the current situation.

(17) One forktruck is shared for both the ADML and adjacent dock.

(18) Maintenance cost of a forktruck based on 4000 engine hours per year, divided between two sharing docks to arrive at the per dock cost.

(19) Annual equivalent maintenance costs of a fork truck per dock.

(20) Forktruck maintenance costs per dock is halved by truck sharing.

(21) Maintenance costs of dock equipment other than forktrucks.

(22) Routine maintenance (takes about 1 hour per week) is recommended.)

(23) Maintenance costs for pneumatic powered roller-tracks.

Sub-Task 6-1-2: Calculate Capability Gains for alternatives:
Using the previously defined equations 6.2 and 6.7, the composite rate of capability gains by each alternative can be calculated. Table 7-9 lists the resultant composite CAPAGAIN

values of each alt_r.

$$d_r^{(ih)} = \frac{M_r^{(ih)} - M_0^{(ih)}}{M_t^{(ih)} - M_0^{(ih)}} \qquad \forall r \qquad (6.2)$$

Total weighted gain by Alt_r is calculated by Equation (6.2):

$$CAPAGAIN_r = \sum_{i=1}^{4} wg_i \left[\sum_{h=1}^{h(i)} wpa_{ih} * d_r^{(ih)} \right] \qquad \forall r \qquad (6.7)$$

Table 7-9. Capability Gain Rate by Alternatives

Performance Measures PA	wpa	M_t	M_0	d_1	d_2	d_3
unload time/trailer (min)	.046	5	45	0	1	1.05
trailer turnround time(min)	.043	35	75	0	1	1
dangers of operator injury	.508	1	5	0	1	1
dangers of goods damages	.09	1	4	0	1	1
dangers of trailer damage	.036	1	5	0	.75	.75
throughput capacity*	.120	6	.8	.77	1.0	1.77
dock facility durability	.023	5	4	0	1	1
equipment life SBOH (khr)	.014	22	10	1	.83	.5
backup readiness (1-5)	.048	5	4	0	0	-3
cargo type handling (1-5)	.002	5	3	0	.5	.5
simple h/m interface (step)	.013	1	3	0	1	1
ease of service (1-5)	.011	5	2	0	.67	.33
operating costs ($000/year)	.002	30	60	0	1	1
forktruck maintenance($k/y)	.018	1.2	2.4	0	1	1
dock maintenance ($/year)	.002	2k	10k	0	1	.25
Composite CAPAGAIN of Alt_r	-	-	-	.106	.912	.853

Sub-Module 6-2: Assess program impacts in other criteria

The implications of the alternatives to the Resource Factors (Transition time and Financial return) and Organizational Factors are assessed through the following sub-task modules:

Sub-Task 6-2-1: Financial assessment of alternatives

The financial assessment for the improvement programs are based on the projected cash flows as in Table 7-10:

Table 7-10. Incremental Financial Requirements of Alternatives (compared with current dock financial performance)

Plant MARR = 20%		Alt 1	Alt 2	Alt 3
Initial investment (installation included) (@$1000)	dock device	30x6 [1]	330 [2]	49.6 [3]
	fork truck	30x6 [4]	-10 [5]	-10 [5]
	trailer modif	none	1x10 [6]	35.5x10 [7]
	training	2.5x6 [8]	.15x4 [9]	.15x4 [9]
Initial investment @$1000		375	330.6	395.2
Operating costs $000/year		60x6 [10]	-60 [11]	-60 [11]
FT Maintenance $000/year		2.38x6 [12]	-2.38 [13]	-2.38 [13]
Dock maintenance $000/yr		10x6 [14]	-8 [15]	-2 [16]
Floor space cost ($000/y)		60 [17]	none	none
Annual cost increments ($1000)		**494.3**	**(70.4)**	**(64.4)**
Study period (# of years)		10	10	10
Salvage value end of 10 yr $1000		-5x6 [18]	-1 [19]	-1 [19]
NPV of costs ($000)		2442.43	35.37	125.12
Project IRR		**-1**	**.1679**	**.1005**

Notes:

(1) Costs for adding 6 sets of dock devices.

(2) Includes shuttleDOCK ($250k) and extras to the system.

(3) Includes one complete dock system, slip chain, dock-lock.

(4) Estimated market price for a fork truck @ $30k each.

(5) Estimated salvage value of a fork truck replaced by the automated unloading/loading devices.

(6) Cost of adding a rack guide to a trailer, by 10 trailers.

(7) Cost for trailer-mounted roller tracks on ten 48' trailer.

(8) Costs of training a fork truck operator by 25 hour OSHA stipulated program @$100 per hour.

(9) Costs of 3 hour on-the-job training sessions for 2 shuttleDOCK operators and 2 maintenance personnel @$50/hour.

(10) Costs of using one fork truck and one driver per dock.

(11) Saving from sharing a fork truck with the adjacent dock.

(12) Annual equivalent fork truck maintenance costs. Service life before overhaul lies between 17000 to 22000 engine hours of a fork truck, thus it is assumed that the fork trucks be overhauled every 5 years. The annual average maintenance costs increase with the engine hours used, as below:

Forktruck maintenance costs vs accumulated engine hours:

year1	year2	year3	year4	year5	annual equivalent (i=20%)
$400	$1000	$2000	$4400	$7000	$2381

(Source: National Services Inc., Material Handling Eng., March 1994)

(13) Savings from maintenance costs due to one less truck.

(14) Maintenance costs of dock devices other than fork trucks, estimated at $10,000 per dock per year.

(15) Savings from dock devices maintenance costs.

(16) Maintenance costs for pneumatic-powered roller-track and slip chain systems, are estimated at $8000 per year.

(17) Each dock takes up floor space of 500sqft @$20/sqft/year.

(18) Estimated salvage value of fork trucks.

(19) Estimated salvage value of automated unloading devices.

Sub-Task 6-2-2: Assessing time requirements of alternatives

Implementation of any alternative program imposes a disruption to the operation norm of the plant, affecting especially the dock productivity. The estimated project time requirements of the three alternatives are summarized in the Table 7-11 below.

Table 7-11. Implementation time requirements by alternatives

Time requirement	Alt_1 $X_{101}=1$, $X_{201}=1$	Alt_2 $X_{202}=1$	Alt_3 $X_{102}=1$
Installation (include concrete works)	8 weeks	4 weeks	6 weeks
Post-installation tuning up and debugging	4 weeks	16 weeks	12 weeks
Operator training	1 week	1 week	1 week
Total implementation time	13 weeks	21 weeks	19 weeks
Relative TRANSITION time (50 weeks/year time base)	0.26	0.42	0.38

Sub-Task 6-2-3: Organizational compatibility of alternatives

At WAP plant the dock area is the interface between the plant and the suppliers. The loading/unloading activities at a dock involve the co-ordinated actions of:

-- A switcher, who is employed by the plant to move the trailers between the dock and the staging yard, also responsible for aligning and centring the trailers against the dock door. The switcher's compensation is based on the number of trailers he moves per shift.

-- A dock operator of WAP plant, who is responsible for opening the dock door, setting the dock-lock, dock-leveller, unloading the full racks from the trailer and stacking the racks in the buffer area beside the dock, transferring the racks to the merging point of the line (the Over/Under system) about 15 meters away from the stacking area, and transferring the empty racks from the line back to the dock to reload unto the trailer. The dock operators are semi-skilled fork-truck drivers working individually one per dock, with little supervision.

-- Maintenance personnel, responsible for minor trouble-shooting and maintenance of equipment. Equipment suppliers can also be called upon if the problem is difficult. The WAP plant has a strong union presence.

The organizational aspects and their degree of importance with respect to implementing the upgrading programs are assessed by the management respondent. The weights of the aspects and their incompatibility levels with respect to the alternatives are summarized in Table 7-12. The degree of incompatibility is assessed according to the following Linguistic Descriptor scale, as defined in Chapter 6:

A:little, B:slight, C:moderate, D:significant, E:total

0, .1, .2, .3, .4, .5, .6, .7, .8, .9, 1.0

The triangle form of fuzzy membership functions defined in Chapter 6 has been adopted in this analysis for quantifying the fuzziness of management respondent's use of the linguistic descriptors. The Quantified Subjective Index (QSI) values are calculated from Eqn.6.13. The QSI values are listed within the brackets in the columns headed with Alt_r (r=1,2,3) in Table 7-12.

Table 7-12. Organizational Impact Assessment

Category	Aspects	As-is system	Incompatibility level		
			Alt 1	Alt 2	Alt 3
Structure (.083)	Job specs (.021)	Single task responsibility	A,1* (.03)	A,1 (.03)	A,1 (.03)
	Work organization (.062)	JIT delivery involving 3 firms, suppliers bear inventory costs	A,1 (.03)	A,1 (.03)	C,4 (.5) 3rd party
Systems (.417)	Training scheme (.275)	On-job training only	C,6 (.5) OSHA req't	A,1 (.03)	A,1 (.03)
	Appraisal & incentives (.065)	Productivity based	A,1 (.03)	A,0 (.03)	A,1 (.03)
	Supervision & control (.077)	Procedure guided solo-operations	A,1 (.03)	A,1 (.03)	A,1 (.03)
Skills (.417)	Range & level (.417)	Narrow routines, Semi-skilled	A,1 (.03)	A,1 (.03)	A,1 (.03)
Culture (.083)	Communication (.034)	Formal channels between functions	A,1 (.03)	A,1 (.03)	A,1 (.03)
	Co-ordination (.04)	Clear turf drawing	A,1 (.03)	B,3 (.25)	B,3 (.25)
	Expected job security (.009)	High job security	A,0 (.03)	C,5 (.5) job cut	C,5 (.5) job cut
Overall ratings of ORGADJUST r			.159	.043	.072

Task-Module 7: Decision Making under Multiple Criteria

-- Synthesizing previous analysis outputs

The module is detailed in Fig.7-15. The four dimensions of the decision criteria calculated individually so far are synthesized in this section by the Compromise Programming method described in Chapter 6. Management was asked to prioritize the decision criteria. The weights and the ideal values of the goals are listed in the Table 7-13 below.

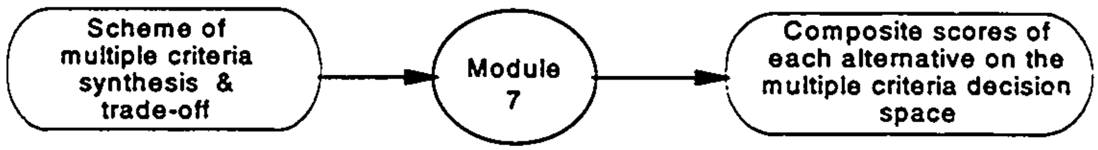
Table 7-13. Goal Values and Objective Function (Distance) Value

Goals	Priority λ	Ideal values	Alt_1	Alt_2	Alt_3
Goal1: CAPAGAIN	.695	1	.106	.912	.854
Goal2: ROI	.110	.20	-1	.1679	.1005
Goal3: TRANSITION	.100	0.1	.26	.42	.38
Goal4: ORGADJUST	.095	0	.159	.043	.072
Composite distances d_p ($p=2^*$)			.6356	.0692	.1061
Recommend as THE improvement program: $\min\{d_p\}$			no	yes	no

(* Note: the power of p=2 is the commonly used parameter.)

Task-Module 8: Elaboration of the Output and Recommendations:

Fig.7-16 illustrates the scores of each alternative along the individual decision criteria in the decision space. Fig.7-17 demonstrates the composite distances of each alternative from the ideal values. Recommendations can thus be made regarding the most appropriate dock improvement program. Installing the Automated-dock-mounted-loading/ unloading system, the



Establish multiple criteria decision making scheme & Synthesize the candidate evaluation results accordingly

What to do:
-Obtain management confirmation and priority ratings of selected decision criteria;
-Apply the decision scheme to the candidates to arrive at final composite scores of each alternative candidate.

How to do:
-Ask management to select and prioritize decision criteria;
-Establish ideal values for each selected criterion;
-Calculate degree of deviation (difference) of each alternative candidate score from the ideal value of the criterion in question;
-Calculate the composite distance of each alternative in the multiple criteria decision space using selected distance defining parameter.

Data format:
-All performance data in comparable relative scale (percentage or fractions)

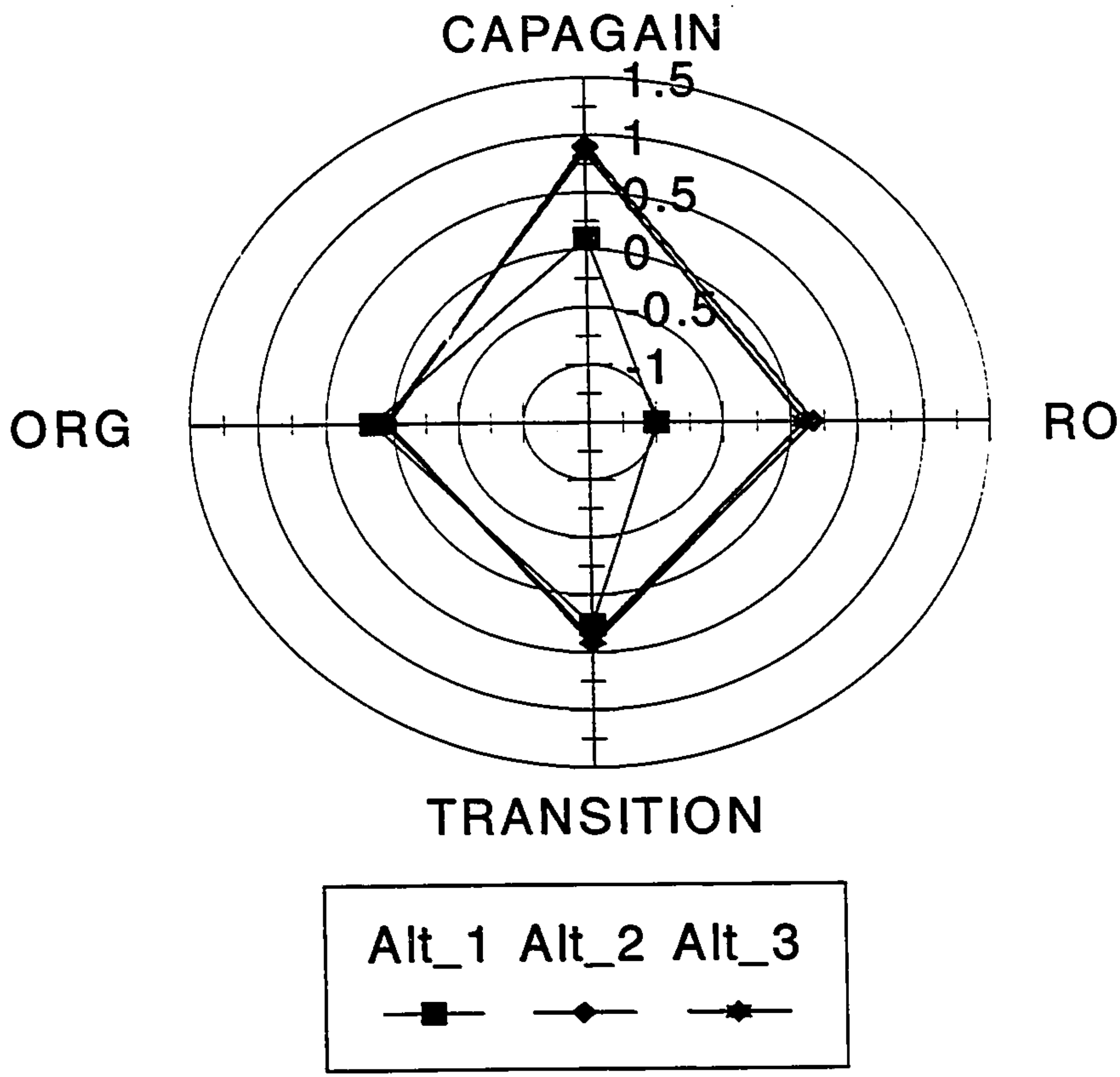
Tools of aid:
- List of decision making criteria commonly used in industry;
- Multiple criteria weighing scheme (eg., AHP package)
- Compromise Programming technique.

Fig. 7-15. Guide for Task Module 7

shuttleDOCK, (Alt_2) is seen to have the minimum composite distance (0.0692) from the ideal values of the criteria, representing the best trade-off among the four decision criteria and management priority in concern. Alt_2 in fact dominates the other two alternatives in all criteria except for the TRANSITION measure in which Alt_2 scores the poorest, ie., it takes longer learning period thanother two to be fully implemented. The preference of Alt_2 over others is mainly justified on its score of 91% achievement in the high-weight criterion of Capability Gain (CAPAGAIN). The Alt_3 is seen to come close in this criterion but for the required modification in the trailers and the resultant decrease in backup readiness (reliability requirement). The rationale behind this CAPAGAIN criterion is the Backcast of performance capability that is needed to support the JIT logistic objectives. Improvement in key capabilities (unloading speed and the dock throughput) would enable further improvement in related areas, such as reduction in the buffer stock level or number of trailers. The upgrade in TE2 is also the pre-condition for further integration of the receiving docks into automated material handling systems in the plant, that is, in TE3.

The financial evaluation of the alternatives is attempted with the estimated costs and savings. Some critical items, such as possible benefits of increased throughput capacity, are excluded due to lack of data; thus the assessment is not

FIG. 7-16. DECISION SPACE



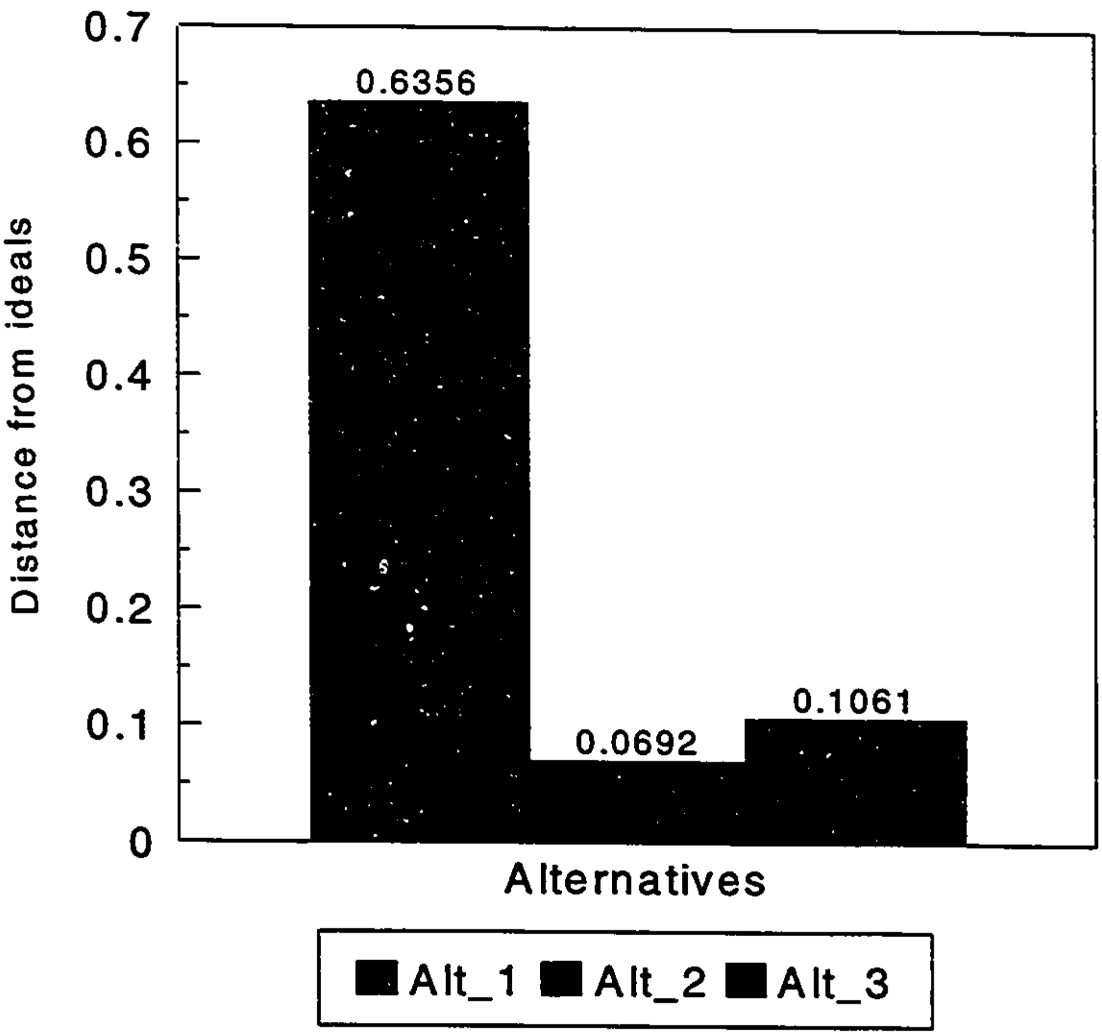


Fig. 7-17. Final recommendation:
by Compromise Programming, Alternative 2 stands out as the most appropriate program for WAP plant dock improvement

complete. The outcome nevertheless indicates the relative cost profiles of the alternatives.

Estimated levels of organizational incompatibility are low with each alternative. In view of the low level of priority of this criterion, influences of organizational considerations are not substantial.

7-2. Summary of the Chapter

In this chapter, the present methodology for planning and justifying acquisition of advanced manufacturing technology in the framework of capability improvement is applied to the real life problem of upgrading dock loading/unloading capabilities in a JIT logistics environment at the WAP plant. The data used in the case came from three sources: a) Direct interviews with the personnel of sufficient knowledge of the study object, b) Direct observation of the operations at the WAP plant, and c) Secondary data from literature and industrial sources like the technology suppliers. The case study has been conducted for two purposes: i) Validating the capability building model of the AMT planning and justification framework; and ii) Illustrating the procedure of applying the presented backcasting methodology in real life situations. This chapter served the second purpose. Chapter 8 will discuss the validity of the model, and the needs for further improvement.

Chapter 8.

Discussions and Conclusions

The methodology of integrated planning and justification of AMT acquisitions will be critically evaluated in this chapter.

8-1. Validity of the methodology

8-1-1. Evaluation of the case study

The case study had two goals, ie., validation of the model, and illustration of the procedure. The second goal has been achieved more satisfactorily than the first one. For example, the case illustrated the task modules of Fig.3-1 step by step and showed that the target (program selection) can be reached when all the modules are executed. The goal of validating the Backcast framework by the case study, on the other hand, has been achieved, but with the following qualifications.

i) Scope of the problem: Of the four basic areas of the technological base as identified in the generic model in Chapter 4, the case only involved a narrow subarea (material handling at receiving docks), due to time and managerial resource constraints, and information accessibility in the correspondent firms. In this respect, the case did not provide sufficient proof of the validity of the framework. Nonetheless, the cross-impacts of the technological program on other factors were discernable in the case, reflecting the specific feature of AMT implementation outlined in Fig.1-1.

The process of assessing the current technological base and identify the bottlenecks is also demonstrated.

ii) Range of input and data reliability: The methodology is shown to be capable of handling both objective or quantitative data and qualitative or subjective inputs, and arriving at final recommendation on these grounds. Types and nature of the input data are dependent on the structuring of the problem. Activity based performance measures, as well as subjective measures of factorial cross-impacts, have been used in the case study. The consideration of 'soft' aspects of implementation requirements, such as the organizational impacts, as well as of certain intangible aspects of dock performances, inevitably resulted in a large proportion of qualitative and subjective data inputs. Table 8-1 summarizes the data requirements of the case study. Subjective estimations had been the only source of data when certain activity-based performance measures were not yet established in the current plant system, but were relevant and needed to be included in the case analysis. This situation is likely to occur in any real world problem. It is assumed that such a mix of subjective and objective data inputs may increase the validity of outputs as compared to the sole use of tangible, quantitative and objective data. It has been advocated that in dealing with uncertainties of this type, "vaguely right" should be preferred to "precisely wrong" [Rosenhead, 1989].

Table. 8-1. Data Input/Output Specifications

Data	Input Requirements			Treatment methods	Output	
Tasks	From	Description	Measures		Description	Measures
MOD 1	Mgt	Bus Strategy Bench marks	QL	Ranking, AHP	Set of objectives, JIT related	QL, 0<wg<1
MOD 2	Mod 1	Weighted objectives (OBJs)	QL & QT as MOD 1	Activity based analysis	Operational performance goals	various as needed
	Mgt	Activities & Performance measures by the OBJs	QL & QT various as needed	AHP	Weights of the goals	[0,1]
MOD 3	MOD 2 Mgt	Targets & Current performance	QL & QT as above	sub-traction	Set of gaps w.r.t. each goal	various as in MOD 2
MOD 4	MOD 2 & 3	Activities, Goals, Gaps	QL & QT	AHP,	Prioritized tech areas	
	Mgt	Current technology base in use	QL	Cause-effect analysis	(bottleneck) for upgrade	[0,1]
MOD 5	Mgt, Vendor survey & MOD4	Details of available tech Alts	QL QT various	Engineering analysis, Act-based cause-effect analysis, Performance estimation	Tech Alts: Configure, Eng.specs, Costs, Skill req'd, Performance expected, Time span	various as needed
MOD 6 Task 6-1	MOD 2, MOD 3, MOD 4	Capability gaps, Estimated performance by Alts	QT, as above	Subtraction	Performance gains by Alt in each goal area	various as above
Task 6-2	MOD 5, MOD 2	Area-based performance gains, Gaps	QT, as above	Division & Weighted sum	Alt Gain Rate in OBJ, Weighted sum of gains	%, and [0,1]

Table. 8-1. Data Input/Output Specifications

Data	Input Requirements			Treatment methods	Output	
Tasks	From	Description	Measures		Description	Measures
MOD 6 Task 6-2	MOD 4, Mgt	Funds req'd Budget goal, Project time estimation, Time base, Disturbance period estimation, Verbal score of organiz'l compatib'ty with Alts	QT & QL, Subjectv, as in MOD 4	Addition, Subtraction & division, Pairwise comparison& Eigenvector weighting, Quantify subjective rating by Fuzzy set	Rate of return, Ratio of transition to basetime, Index of Organization adjustment required	%, % [0,1]
MOD 7	MOD 6,	Gain rates, Cross impact between Alts and other factors Ideal Goal Values	QT, as above	Compromise Programming with chosen parameters & priorities	The Alt_r* that minimizes composite distances from ideals	unitless score of distance value
MOD 8	MOD 7	Final choice	QL	Management decision	Tech programs	QL

(MOD = task module; QL=qualitative; QT=quantitative; OBJ=objectives)

<u>iii) Generalization feasibility</u>: One of the objectives of this research is to develop an AMT planning and justification methodology that is applicable to real life situations. The case study demonstrated the accomplishment of this objective to a limited extent. While the chosen case has focused on a specific area of activity in a large production system, the structure of the proposed framework is capable of handling larger size problems, <u>provided that</u> the boundary of the system can be defined, and a <u>multi-disciplinary team</u> can be organized to take on the tasks of data collection and analysis. The methodology can in fact be said to resemble the quality

improvement process (QIP) in Total Quality Management (TQM); therefore QIP guidelines for selecting manageable problems to tackle may also apply.

iv) Application potential: Although the methodology has been developed for manufacturing firms to assess their own manufacturing capabilities and planning for AMT acquisition, the case study proved that the methodology can also be used as a marketing tool for a technology vendor to assess customers' needs and to appropriately customize the technology choice.

8-1-2. Validity of hierarchical structuring and backcasting

The case study shows that the **backcast framework** facilitates AMT planning and justification efforts by first focusing managerial attention on strategic objectives, such as pursuit of JIT production, and translating the objectives into dock operational details that determine the docks' capability to support JIT production in the plant. *Justification is built into the process* since the most appropriate alternative is identified on the basis of its closest positioning with respect to the capability targets, as shown in Fig 7-17. Hierarchical structuring of problems is shown to be acceptable to the practitioners in industry as being viable for modelling the reality. The clusters in the hierarchy are case dependent.

8-1-3. Type and role of the output

The methodology is shown to be capable of distinguishing between alternative programs according to a set of decision criteria, and leading to a recommendation of the most appropriate program in the given context by a single composite score that can be demonstrated graphically and understood by decision makers (Fig.7-16 & Fig.7-17). The methodology facilitates the decision on acquisition of advanced manufacturing technology, in this case the automated loading/unloading technology, by focusing managerial attention on programs' capability improvement potential rather than on financial projections alone (Fig.7-14).

8-1-4. Assessing the output robustness by sensitivity analysis

The output of the model depends on the given values of model parameters, in particular, on:

i) Estimation of the performance levels of the alternatives.

ii) Priority weights of the Influencing Factors in the model;

iii) Priority weights $\{\lambda_i\}$ of the decision criteria in the MCDM objective function.

The performance estimations are mainly activity-based physical measures. These are least affected by the decision makers' subjective bias, and thus may have less impact on robustness of the output. The last two categories of parameters are, however, decision makers' subjective inputs that are prone to bias and error, and hence play major roles in the robustness of the decision (Table 7-12 and Table 7-13). Impacts from these sources can be restricted through a) internal mechanism, and b) execution of the methodology. Internally, derivation of these weights through AHP eigenvector method has the built-in mechanism for assuring consistency of decision makers' judgements, indicated by the Consistency Ratio (CR), as shown in Chapter 4 (Section 4-3-3). Theoretically, CR<0.10 should be maintained whenever possible. In the case study, some weights were accepted with CR>0.10 due to the managerial respondents' limited time commitment. In real problem solving the CR check should be satisfied by iteration. Externally, the backcast process can only be carried out as team efforts due to its multi-functional nature; thus, the outputs are less affected by individual biases.

If necessary, sensitivity analysis can also be conducted by altering the sets of priority weights of the factors and decision criteria, while maintaining proper CR check, or even eliminating certain factors, in order to find out the range of decision maker preferences wherein the particular final recommendation remains unchanged. For example, the case result will not change if the criterion ORGADJUST is removed (ie., $\lambda_4=0$) (Table 7-13).

8-2. Comparison of the Backcasting with conventional financial justification approach

In the case study the backcasting and conventional financial DCF analysis identified the same alternative as the best choice. This coincidence should not be generalized. In the present situation, the cost components as identified by the participating industry contributed to this finding. A contrast of the Backcasting framework with the conventional financial justification approach is shown in Table 8-2:

Table 8-2. Comparison of Frameworks

	Financial Justification	Capability based Backcasting Approach
Question to be answered:	How much return can AMT investment generate?	How desirable future position can be reached?
Nature:	positive (project-worth evaluation, referencing to stated financial criterion)	normative (goal setting and path prescribing) from futures to present, with built-in justification
Focus:	ROI, financial opportunity costs	gap closing potential and feasibility
Execution time scale:	ad hoc, project specific	iterative planning cycles
Analysis:	DCF, comparison with "best possible alternatives" of specified rate of return	interpolation from set goals to as-is position, anchored in capabilities
Input requirement:	all quantitative, dollarized values	qualitative as well as quantitative data
Output quality	dependent on completeness and accuracy of cash-flow projection	implication oriented, can tolerate vague information

Backcasting framework is thus shown to be advantageous over conventional financial justification approaches in that:
i) It shifts the focus away from solely financial results by asking the critical question about a firm's capability positioning in the future; hence it fulfils the reform needs identified in Chapter 1 (page 1);
ii) It prescribes capability improvement paths rather than simply assessing the results, and is thus applicable as a planning tool as well as an evaluation mechanism;
iii) It incorporates a wider range of parameters than the financial approach, thus providing management with a better understanding of the implications of improvement programs;
iv) It has the capacity to handle qualitative and intangible aspects of AMT acquisition, rather than merely quantitative and tangible data, thus overcoming difficulties in attempting to define all potential benefits and costs of AMT programs in monetary terms.

8-3. Conclusion and Future Work

The specific objectives of the present research, stated in Chapter 2, have been accomplished in this thesis. A framework for planning and justification of AMT acquisitions has been developed, which adopts activity-based performance measures as the indicators of manufacturing capabilities, and derives the most appropriate capability improvement program through the

Backcast process. The case study demonstrates that the methodology is feasible for application in real life situations, and can be adapted to individual cases. The implementation procedure for the framework is modularized for user convenience. Comments from the industrial participants of the case study have been positive. The methodology is shown to be a step forward in reforming AMT investment justification methodologies.

Appropriate data input is critical for application of the methodology. Relevant and reliable data can only be obtained from in-depth analysis and thorough comprehension of the systems and problems. It is believed that the robustness of decision support by this method will be enhanced by:

a) **Coordinated team efforts** in real case implementation;

b) **Development of a computer based decision support tool** that allows simpler and user-friendly interactions between analysts and the model's internal functions, and facilitates the communication between the analysts and decision makers. This will be the focus of future research efforts.

Appendix I

Questionnaire

Questionnaire:

The following questions are designed for acquiring information to be used for validation of the proposed framework. All information will be kept strictly confidential, the respondent company will be kept anonymous and its profile is for background assessment only. Please fill in the blanks as much as possible. Your kind assistance is much appreciated.

Part 1: Company (Division) Profile -- For background information

Industry: (AUTOMOTIVE)
Product lines: (LINCOLN CONTINENTAL; LINCOLN TOWN CAR)
Size of workforce:
  # of operators: skilled(___);non-skilled(___);
  # of engineers: design & engineering(___); manufacturing(___); service & support(___)
Position with respect to major competitors:
  smaller(___); same league(X); larger(___);
Number of Major customers: (1500)
Industries of major customers: (AUTO DEALERS, FLEET SALES)
Number of Major suppliers: (20)
Mandated rate of return on investment in technology: MARR=(____)%.

Part 2: Products and production operation mode

Range of major product lines: (name: AUTOMOBILES)
  # of models is (2).
  average # of variants per model is (60).
Production operation types:
  (90) % made to order, (10) % made to stock.
Production volumes and Rates:
(__)%@ less than 100 unit/month, (__)%@100-1,000 unit/month,
(X)%@1,000-10,000 unit/month, (__)%@ over 10,000 units/month

New product introduction rate: (2) per year
Ratio of aggregate volume Q to number of models P: Q/P=(______)

Part 3: Company's Logistics pattern

JIT production & inventory management mode JIT: Yes(X), No(__).
Manufacturing facility site: single(X), multiple(__).
Warehousing operation: centrallized(__), distributed(__). NONE
Number of docks: (2) per loading/unloading point.
Type of transportations: Truck/trailer(X)%, Railroad(__)%.
Types of cargos shipped/received:
  finished_product(__)%, semi_finished(X)%, components(X)%.
Cargo conditions:
palletized(__)%, loose_packs(__)%, palletized_box(_)%, bulky(__)%.
Volumes of cargo: (60) of trucks per warehouse per week. RACKS(X).

Part 4: Company's logistics objectives

Following Objectives and performance measures are 'by default':

1) Please check those relevant to your firm's strategies, add any others objectives that you would pursue for next 5 years;

2) Rank the priorities by assigning to each entry (row-column pair) a value from 1-9, or its reciprocal, according to following scales:

1=equal importance of both elements;
3=weak importance of one element over another;
5=essential or strong importance of one over another;
7=very strong or demostrated importance;
9=absolute importance of one element over another;
2,4,6,8=intermediate values between adjecent scale values;
Reciprocals of above nonzero values: $a_{ij} = 1/a_{ji}$

Objectives	A)	B)	C)	D)	E)	F)	G)	H)
A) Efficiency	1	1/7	1/5	5	7	9		
B) Safety	-	1	9	9	9	9		
C) Reliability	-	-	1	7	7	9		
D) Flexibility	-	-	-	1	1	1		
E) Low costs	-	-	-	-	1	5		
F) Security	-	-	-	-	-	1		
G) Others	-	-	-	-	-	-	1	
H)	-	-	-	-	-	-	-	1

Part 5: Operational objectives in Dock loading/unloading activities

The above broad warehousing_logistics functional objectives may be translated into sub-objectives in loading/unloading activities:

a) Please check relevance and rank your priorities of the sub-objectives;

Objective	Operational objectives (Performance measures)	Priority scores: 1-9 or reciprocal			
		a	b	c	d
Efficiency	a) load/unload speed	1	7	1	9
	b) low human intervention	—	1	1/5	1
	c) high truck turnaround	—	—	1	9
	d) AS/RS interface	—	—	—	1

b) Please check relevance and rank your priorities of the sub-objectives;

Objective	Operational objectives (Performance measures)	Priority scores: 1 to 9 or reciprocal			
		e	f	g	h
Safety	e) No danger to people	1	9	9	
	f) No damage to loads	1/9	1	4	
	g) No damage to trucks	1/9	1/4	1	
	h) others	—	—	—	1

c) Please check relevance and rank your priorities of the sub-objectives;

Objective	Operational objectives (Performance measures)	Priority scores: 1 to 9 or reciprocal				
		i	j	k	l	m
Reliability	i) Throughput capacity	1	7	7	3	
	j) Durability of docks	1/7—	1	1	1	
	k) Eqpt life (SBOH)	1/7—	—	1	1/7	
	l) Backup readiness	1/3—	—	7	1	
	m) others					1

d) Please check and rank the sub-objectives by their level of priorities;

Objective	Operational sub_objectives	Priority scores: 1 to 9 or reciprocal					
		n	o	p	q	r	s
Flexibility	n) wide truck range	1	1	1	1	1/9	1/7
	o) wide load range	—	1	1	1	1/9	1/7
	p) equipment mobility	—	—	1	1	1/9	1/7
	q) load from sides	—	—	—	1	1/9	1/7
	r) simple interface	—	—	—	—	1	1
	s) easy maintenance	—	—	—	—	—	1

e) Please check relevance and rank your priorities of the sub-objectives;

Objective	Operational objectives (Performance measures)	Priority scores: 1 to 9 or reciprocal			
		t	u	v	w
Low_costs	t) Initial costs	1	5	1/5	
	u) Operating costs	—	1	1/7	
	v) Maintenance costs	—	—	1	
	w) Others				1

f) Please check relevance and rank your priorities of the sub-objectives;

Objective	Operational objectives (Performance measures)	Priority scores: 1 to 9 or reciprocal	
		x	y
	x)	1	
Others	y)		1

Part 6: Current vs Target performance levels in loading/unloading operations

Please fill in relevant performance data: Current & Target levels

Hint: For performances whose measurements are not available, or data are not obtainable, please give a subjective judgement by the following scale:
1=low; 2=lower medium; 3=medium; 4=higher medium; 5=high

Performance measures	current	benchmark	target	gap (t-c)
a) load/unload time/truck (min)	45	35	5	-40
b) human intervention/load (min)	75	15+10	15+10	-50
c) truck turnaround time (min)	75	60	35	-40
d) AS/RS interface possibiliy	MANUAL.)	✓	5	4
e) dangers, people injury/period	5	✓	1	-4
f) dangers, load damaged/period	4	✓	1	-3
g) dangers, truck damaged/period	5	✓	1	-4
h) others				
i) Throughput capacity (Truck/hour)	.8	✓	6	5.2
j) Dock facility durability	4	✓	5	1
k) Equipment life (SBOH) [hr]	10,000	✓	22000	12000
l) Backup facility ~~type~~ (Readiness)	Adjacent Dock 3	✓	5	2
m) others				
n) truck range handled	5	Dedicated Fleet	5	n/c
o) load range handled	3	Dedicated Racks	5	2
p) (mobile : fixed) Mobility	5	Fixed	5	n/c
q) load from sides (y/n)	N	✓	N	n/c
r) simple interface ([illegible])	3	—	1	-2
s) standard components (easy maint.)	2	—	5	3
t) Initial costs	$30,000	(Dock device)	—	—
u) Operating costs per dock	$60,000	(Forktruck + Driver)	$30,000*	-$30000
v) Maintenance costs	$10,000		$2,000	-$8000

Cut back use of Forktruck by one. Two adjacent docks may share one truck.

Part 7: Existing Dock_Loading/Unloading systems profile

(To identify any bottleneck technological subareas-- for Step 3 & Step 4 Inputs) Technological base may be decomposed into subareas in column 1. Please **Check** and **Add** relevant items in columns 2, 3, 4, and Causal Links of subareas to the gaps:

5-1) Dock area activities and automated loading/unloading tools in use:

Sub areas	Tool types	Activities supported	Functional limits	Causal link to gaps
Dock mechanical devices Goods Handling devices Goods transfer devices	Trailer leveler(__) Dock floor leveler(X) Dock_lock((X) Forklift(X) Robots(__) Special tools(_) Forklift(X) Robots(__) Special tools(__)	Truck alignment(X) Trailer_centering(X) Truck_leveling(__) Dockfloor_leveling(X) Trailter_securing(X) Load_centering(X) Auto_loading(X) Auto_unloading(X) Goods_stacking(X) Goods_transfer(X) Palletized_workpiece handling(X) Loads_orientation(X) Goods_transfer(____)	Trailer size: 53' Trailer orientation Rear load Goods orientation Pallet type Dedicated racks	Loading speed Unloading speed ✓ Truck turn round time ✓ Operatr safety ✓ Goods damage ✓ Trailer damage ✓
AS/RS facility & interface Sensors & Controls	Fork truck (X) Conveyors(__) Robots(__) AGVs(__) AS/RS_special tools(X) —(OVER/UNDER SYSTEM) #_of_data_types (___) Online(_), Offline(__) Data_down_load: local(X), remote(__) Control_types: auto(__) manual(X)	Palletized_workpiece handling(X) Goods_orientation(✓) Goods_transfer(✓) Trailer_presence(X) Goods_positioning(__) Goods_conditioning(_) Forces(__) Movement(__)		Handling scope Waiting time ✓ Moving time ✓ Damage rate MTOI (mean time between operator intervention) Safety ✓ Damage rate
Dock layout: STAGED IN A YARD WHEN	* NOTE: TRAILERS ARE STAGED IN A YARD WHEN DELIVERED FROM	Capacity: (200) trucks/month Peak hour occupancy: (100) % * Distance to storage:	Avg distance moved: Stacking area:	Moving time 10 min Waiting time 60 min Inventory ** (EMPTY RACKS) Cost_nonvalue adding

SUPPLIER. SWITCHER TRACTOR BRINGS NEW TRAILER AS REQD. (APPROX 1 PER HR)

1/4 MILE

(** 8 TRAILERS PER SUPPLY = 1 on Dock 2 STAGED ON LINE 5 IN YARD.)

Part 8: Attributing major performance gaps to loading/unloading facility

Relate each major gap (part 5) to the categories of technological functions according to the following scale of 0-9:

0=unrelated; 1=weakly related; 3=moderately related; 5=strongly related; 7=very strongly related; 9=absolutely related.

Not distinct

Performance measures	Dock. device	Goods. 909 handling	Goods .597 transfer	AS/RS .134 interface	Sensor& control
a) load/unload time/truck .456	1	9	5	1	1
b) human intervention/load .067	0	9	3	0	7
c) truck turnaround rate .423	1	9	7	1	0
d) Interfacing AS/RS .054	5	9	9	9	9
e) people injury/period .82	5	9	1	0	
f) load damaged/period .142	3	9	3	3	
g) truck damaged/period .376	3	9	0	0	
h) others	(4.600	9	1.23	.426)	
i) throughput capacity .585	1	9	5	0	
j) dock durability .114	5	7	0	0	
k) eqpt life (SBOH) .358	0	9	9	5	
l) backup facility type .223	0	9	0	1	
m) others	(1.16	9.68	2.93	1.15)	
n) truck range handled .5			0	0	
o) load range handled .5	3	9	3	0	
p) mobile : fixed .05					
q) load from sides (y/n) .5					
r) simple interface .433	3	7	7	1	
s) standard components .366	3 1.35	9 6.78	5 5.04	3 1.23	
t) Initial costs .219					
u) Operating costs/month .067	1	9	5	7	
v) Maintenance costs/month .715	3	9	9	7	
w) Others	(2.21	7.04	6.11	5.07)	
x)					

Part 9: Identify technological alternatives for system upgrading

a) Technological Alternative (Alt) Configuration Specifications: for STEP 4

Tech Alts	Name of candidate systems	Descriptions of Scope and Characteristics					
		Dock device	Goods handling	Goods transfer	AS/RS interface	Sensor& control	Dock Layout
Alt_1	BUILD 6 MORE DOCKS (OLD Type)	AS-IS	AS-IS (FORKTRUCK)	AS-IS FORKTRUCK	AS-IS	AS-IS	AS-IS
Alt_2	DOCK MOUNTED AUTO-UNLOADING DEVICE	AS-IS NET DOCK LEVELER	SHUTTLEDOCK	FORK TRUCK	AS-IS	AS-IS + FORCE	AS-IS
Alt_3	DOCK + TRUCK MOUNTED DEVICE	ROLL-A-TRACK SLIP-CHAIN →		AS-IS	AS-IS	AS-IS	AS-IS

b) Projected performance upgrading levels by alternatives

Performance measures	Target	Alt_1	Alt_2	Alt_3	
a) load/unload time/truck	5 min	45 min	5	3	
b) human intervention/load	25 min	75	25	25	
c) truck turnaround rate	75 min	60	35	35	
d) Interfacing AS/RS	5 (High)	1 (Manual)	5 (Automatic proposed)	5	
e) people injury/period	1* (Low)	5 (High)	1	1	
f) load damaged/period	1	4	1	1	
g) truck damaged/period	1	5	2 (May hit Trailer)	2 (Trailer must be modified)	
h) others					
i) throughput capacity	6/hour	4.8/h	6/h	10/h	
j) dock durability	5	4	5	5	
k) equpt life (SBOH)	22000h	22500	20000	16000 (pneumatic system)	
l) backup facility type	Standard Fork Truck	ForkTruck	Fork Truck Adjacent Dock	Manual	
m) others					
n) truck range handled	Dedicated	—	—	—	N/c
o) load range handled	5	3	4	4 (Dedicated Racks)	
p) mobile : fixed	Fixed	—	—	—	NE
q) load from sides (y/n)	N	N	N	N	NE
r) simple interface Operating Steps	Single Step	3 Step	1 Step	1 Step	
s) standard components ease of Maintenance	5	2 (Skilled Mechanic)	4 (Simple Routine)	3	
t) Initial costs	Not determined	—	—	—	
u) Operating costs	$30,000	$60,000	$30,000	$30,000	
v) Maintenance costs Fork Truck	$1,200/Year	$2400**/Year	$1200	$1200	
w) Others Dock Maintenance	$2,000/yr	$10,000/Year	$2,000/Yr	$8,000/Year	

** Equivalent Annual Maintenance Cost for ForkTruck. Six of this are needed.

Maintaining pneumatic Roller-Track Systems.

Part 10: Decision makers' priorities associated with decision criteria

(For multiple-criteria-decision-making)

a) Would you consider the following criteria relevant for evaluating a technology acquisition proposal? Please add any other criteria relevant to your firm:

b) Please rank priorities of the relevant goals by pairwise comparison and assign numerical score of 1 to 9 (or reciprocal) to each pair of goals as follows:

Importance to AMT acquisition	Capability gain	ROI	Transition time	Organization compatibility	Others
Performance Capability gain	1	5/1	7/1	9/1	
ROI (target=20%)	-	1	1	1	
Transition time	-	-	1	1	
Organization compatibility	-	-	-	1	
Others:	-	-	-	-	1

Part 11: Implementation requirements for Tech_Alternatives:

Tech Alts	Implementation requirements				Capital investment required ($/1000)
	Installation time (# of weeks)	Post_install learning period (wks)	Personnel change (# of operators required)	Personnel change (# of job roles & skill levels)	
Alt_1	8 weeks	1+4 weeks	N/C, (one per dock/sh.)	Forktruck Driver Training	375
Alt_2	4 weeks	1+16 weeks	-1 (one on 2 adjacent docks)	N/C	330.6
Alt_3	6 weeks	1+12 weeks	-1 (One man on 2 docks)	N/C	395.2

Part 12: Warehouse organizational profile for compatibility assessment

Organization of workforces at the receiving docks:
as work group of (__) people, as individual(✓)

Scope of dock operator responsibilities:
(100)%operating, (__)%operating+problem_solving,
(__)%operating+problem_solving+maintenance

? Skill ranges of operators:
(✓) % single_eqpt, (__) % two_eqpt, (__) % three or more eqpt

Skill levels of operators:
(__)% unskilled, (100)% semi-skilled, (__) % skilled

Training systems in use:
(__)weeks_induction, (__)weeks retraining per year,
(✓)on_job_training_only (Operators)
(special sessions for maintenance)

Part 13. Identify and rate the organizational categories:

1) Please check those relevant to your firm, add any other elements that you consider important for implementing the proposed technological change;

2) Please respond to the question: With respect to implementing the technology changes, how many times area i is as important as area j?
Mark your answers by assigning to each entry (row-column pair) a value of 1-9, or its reciprocal, according to the scales described in Part 3:

Importance to implementation	Structure	Systems	Skills	Culture	Others
Structure	1	1/5	1/5	1	
Systems	-	1	1	5	
Skills	-	-	1	5	
Culture	-	-	-	1	
Others	-	-	-	-	1

Importance to Structure	Job Specs	Work Organization	others	
Job specs	1	1/3		
Work organization	-	1		
others	-	-	1	

Importance to Systesms	Training	Appraisal	Supervision	Planning	others	
Training	1	5/1	3/1			
Appraisal	-	1	1			
Supervision	-	-	1			
~~Planning~~ ?	-	-	-	1		
others	-	-	-	-	1	1

Importance to skills	Range & levels	Upgradability	others	
Range & levels	1			
~~Upgradability~~ ?	-	1		
others	-	-	1	

Importance to cultural envt	Communica formality	Coordina- tion	Participa- tion	People policy	others	
Communication formality	1	1		3/1		
Coordination	-	1		5/1		
? ~~Participation level~~	~~-~~	~~-~~	~~1~~			
People policy	-	-	-	1		
others	-	-	-	-	1	

Part 14: Organizational Incompatibility assessment:

According to your opinion, what is the degree of **Incompatibility** of a Technological Alternative to the organizational attributes in the column 2 below?

Note: For each criteria in column 2, please assign to each Alts a verbal descriptor and a numerical score value as follows:

A: Little, B: slight, C: moderate, D: significant, E: total
0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

Categories	Attributes	Alt_1	Alt_2	Alt_3
	(example:)	(B,3)	(D,8)	(D,7)
Structure	Job specs	A. 1	A. 1	A. 1
	Work organization	A. 1	A. 1	C. 4 (changes in 3rd party [illegible])
Systems	Training	C. 6 (Regulation [illegible])	A. 1	A. 1
	Appraisal&incentive	A. 1	A. 0	A. 1
	Supervision&control	A. 1	A. 1	A. 1
	~~Planning&scheduling~~			
Skills	Range & levels	A. 1	A. 1	A. 1
	~~Upgradability~~			
Culture	Communication formality (between Functions)	A. 1	A. 1	A. 1
	Coordination	A. 1	B. 3	B. 3
	~~Participation~~			
	Personnel policy	A. 0	C. 5 (Cut jobs)	C. 5 (Cut jobs)

Thank you for your help!

Appendix II

Pairwise Comparisons and Priority Weights

-- Output of AHP Analysis

Table 2. Model Structure, Weights, Shares, and Inconsistency Ratios

CATEGORY	CRITERION	WEIGHT	SHARE	RATING INCONSISTENCY
EFFICIEN	Speed	0.456	0.046	0.000
	HumanInt	0.067	0.007	0.000
Weight = 0.101	TruckUse	0.423	0.043	0.000
Inconsistency = 0.012	Interfac	0.054	0.005	0.069
SAFETY	People	0.802	0.508	0.000
	Goods	0.142	0.090	0.000
Weight = 0.634	Trucks	0.056	0.036	0.005
Inconsistency = 0.187*				
RELIABLE	DockLife	0.114	0.023	0.000
	EqptLife	0.068	0.014	0.000
Weight = 0.205	Capacity	0.585	0.120	0.000
Inconsistency = 0.140*	Backup	0.233	0.048	0.061
FLEXIBLE	Trucktyp	0.050	0.002	0.061
	Loadtype	0.050	0.002	0.011
Weight = 0.031	Mobility	0.050	0.002	0.101*
Inconsistency = 0.001	Sideload	0.050	0.002	0.000
	Simple	0.433	0.013	0.011
	Standard	0.366	0.011	0.000
LOW COST	Initial	0.219	0.007	0.000
	Operatin	0.067	0.002	0.000
Weight = 0.030	Maintenc	0.715	0.021	0.056
Inconsistency = 0.158*				

[Inconsistency of pairwise comparisons between categories = 0.196*]

*Pairwise comparisons with inconsistency values > 0.1 should be redone.

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Categories

	Efficien	Safety	Reliable	Flexible	Low cost
Efficien		0.143	0.200	5.000	7.000
Safety			9.000	9.000	9.000
Reliable				7.000	7.000
Flexible					1.000
Low cost					

Comparisons between Criteria within Category: Efficien

	Speed	HumanInt	TruckUse	Interfac
Speed		7.000	1.000	9.000
HumanInt			0.200	1.000
TruckUse				9.000
Interfac				

Comparisons between Criteria within Category: Safety

	People	Goods	Trucks
People		9.000	9.000
Goods			4.000
Trucks			

Comparisons between Criteria within Category: Reliable

	DockLife	EqptLife	Capacity	Backup
DockLife		1.000	0.143	1.000
EqptLife			0.143	0.143
Capacity				3.000
Backup				

Comparisons between Criteria within Category: Flexible

	Trucktyp	Loadtype	Mobility	Sideload	Simple	Standard
Trucktyp		1.000	1.000	1.000	0.111	0.143
Loadtype			1.000	1.000	0.111	0.143
Mobility				1.000	0.111	0.143
Sideload					0.111	0.143
Simple						1.000
Standard						

Comparisons between Criteria within Category: Low cost

	Initial	Operatin	Maintenc
Initial		5.000	0.200
Operatin			0.143
Maintenc			

Comparisons between Alternatives rated by Criterion: Speed

[See Table 5 for Performance Data]

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Alternatives rated by Criterion: HumanInt

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: TruckUse

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: Interfac

	Shuttle	MoreDock	RollTrac
Shuttle		7.000	3.000
MoreDock			1.000
RollTrac			

Comparisons between Alternatives rated by Criterion: People

	Shuttle	MoreDock	RollTrac
Shuttle		7.000	1.000
MoreDock			0.143
RollTrac			

Comparisons between Alternatives rated by Criterion: Goods

	Shuttle	MoreDock	RollTrac
Shuttle		5.000	1.000
MoreDock			0.200
RollTrac			

Comparisons between Alternatives rated by Criterion: Trucks

	Shuttle	MoreDock	RollTrac
Shuttle		5.000	1.000
MoreDock			0.250
RollTrac			

Comparisons between Alternatives rated by Criterion: DockLife

	Shuttle	MoreDock	RollTrac
Shuttle		1.000	1.000
MoreDock			1.000
RollTrac			

Comparisons between Alternatives rated by Criterion: EqptLife

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: Capacity

[See Table 5 for Performance Data]

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Alternatives rated by Criterion: Backup

	Shuttle	MoreDock	RollTrac
Shuttle		0.200	4.000
MoreDock			9.000
RollTrac			

Comparisons between Alternatives rated by Criterion: Trucktyp

	Shuttle	MoreDock	RollTrac
Shuttle		0.200	4.000
MoreDock			9.000
RollTrac			

Comparisons between Alternatives rated by Criterion: Loadtype

	Shuttle	MoreDock	RollTrac
Shuttle		0.200	1.000
MoreDock			7.000
RollTrac			

Comparisons between Alternatives rated by Criterion: Mobility

	Shuttle	MoreDock	RollTrac
Shuttle		0.200	5.000
MoreDock			9.000
RollTrac			

Comparisons between Alternatives rated by Criterion: Sideload

	Shuttle	MoreDock	RollTrac
Shuttle		0.111	1.000
MoreDock			9.000
RollTrac			

Comparisons between Alternatives rated by Criterion: Simple

	Shuttle	MoreDock	RollTrac
Shuttle		7.000	1.000
MoreDock			0.200
RollTrac			

Comparisons between Alternatives rated by Criterion: Standard

	Shuttle	MoreDock	RollTrac
Shuttle		0.333	1.000
MoreDock			3.000
RollTrac			

Comparisons between Alternatives rated by Criterion: Initial

[See Table 5 for Performance Data]

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Alternatives rated by Criterion: Operatin

	Shuttle	MoreDock	RollTrac
Shuttle		5.000	1.000
MoreDock			0.200
RollTrac			

Comparisons between Alternatives rated by Criterion: Maintenc

	Shuttle	MoreDock	RollTrac
Shuttle		7.000	3.000
MoreDock			0.200
RollTrac			

Table 5. Performance Data for Rating Alternatives

CRITERIA	ALTERNATIVES			IS HIGHER
	Shuttle	MoreDock	RollTrac	BETTER?
Speed	5	35	3	No
HumanInt	25	70	25	No
TruckUse	2	1	2	Yes
Interfac	[See Table 4 for Pairwise Comparison Data]			
People	[See Table 4 for Pairwise Comparison Data]			
Goods	[See Table 4 for Pairwise Comparison Data]			
Trucks	[See Table 4 for Pairwise Comparison Data]			
DockLife	[See Table 4 for Pairwise Comparison Data]			
EqptLife	20000	20000	10000	Yes
Capacity	600	86	1000	Yes
Backup	[See Table 4 for Pairwise Comparison Data]			
Trucktyp	[See Table 4 for Pairwise Comparison Data]			
Loadtype	[See Table 4 for Pairwise Comparison Data]			
Mobility	[See Table 4 for Pairwise Comparison Data]			
Sideload	[See Table 4 for Pairwise Comparison Data]			
Simple	[See Table 4 for Pairwise Comparison Data]			
Standard	[See Table 4 for Pairwise Comparison Data]			
Initial	330000	150000	350000	No
Operatin	[See Table 4 for Pairwise Comparison Data]			
Maintenc	[See Table 4 for Pairwise Comparison Data]			

Table 1. Ranking of Alternatives by Overall Rating

```
RANK  ALTERNATIVE  RATING

=>1   TE2          0.635  ||||||||||||||||||||||||||||||||||||||||||||||||||

  2   TE1          0.165  ||||||||||||

  3   TE3          0.151  |||||||||||

  4   TE4          0.051  |||
```

Table 2. Model Structure, Weights, Shares, and Inconsistency Ratios

CATEGORY	CRITERION	WEIGHT	SHARE	RATING INCONSISTENCY
JIT DOCK	SPEED	0.101	0.101	0.049
	SAFETY	0.634	0.634	0.107*
Weight = 1.000	RELAIBLE	0.205	0.205	0.092
Inconsistency = 0.196*	FLEXIBLE	0.031	0.031	0.092
	LOWCOST	0.030	0.030	0.089

[Inconsistency of pairwise comparisons between categories = 0.000]

*Pairwise comparisons with inconsistency values > 0.1 should be redone.

Table 3. Ratings by Criterion and Overall Ratings of Alternatives

CATEGORY: CRITERION	RATINGS TE1	TE2	TE3	TE4
1: SPEED	0.055	0.669	0.220	0.055
1: SAFETY	0.213	0.623	0.123	0.041
1: RELAIBLE	0.102	0.662	0.171	0.065
1: FLEXIBLE	0.056	0.646	0.244	0.054
1: LOWCOST	0.049	0.556	0.259	0.136
OVERALL RATING	0.165	0.635	0.151	0.051

Table 2. Model Structure, Weights, Shares, and Inconsistency Ratios

CATEGORY	CRITERION	WEIGHT	SHARE	RATING INCONSISTENCY
CAP-GAIN Weight = Inconsistency = 0.000	Cap-Gain	1.000	0.695	0.000
RETURN Weight = Inconsistency = 0.000	Return	1.000	0.110	0.000
PROTIME Weight = Inconsistency = 0.000	ProTime	1.000	0.100	0.000
ORGCHANG Weight = Inconsistency = 0.000	OrgChang	1.000	0.095	0.000

[Inconsistency of pairwise comparisons between categories = 0.000]

*Pairwise comparisons with inconsistency values > 0.1 should be redone.

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Categories

	Cap-Gain	Return	ProTime	OrgChang
Cap-Gain		5.000	7.000	9.000
Return			1.000	1.000
ProTime				1.000
OrgChang				

Comparisons between Criteria within Category: Cap-Gain

	Cap-Gain
Cap-Gain	

Comparisons between Criteria within Category: Return

	Return
Return	

Comparisons between Criteria within Category: ProTime

	ProTime
ProTime	

Comparisons between Criteria within Category: OrgChang

	OrgChang
OrgChang	

Comparisons between Alternatives rated by Criterion: Cap-Gain

[Not Rated]

Comparisons between Alternatives rated by Criterion: Return

[Not Rated]

Comparisons between Alternatives rated by Criterion: ProTime

[Not Rated]

Comparisons between Alternatives rated by Criterion: OrgChang

[Not Rated]

Table 2. Model Structure, Weights, Shares, and Inconsistency Ratios

CATEGORY	CRITERION	WEIGHT	SHARE	RATING INCONSISTENCY
STRUCTUR	Job spec	0.250	0.021	0.000
Weight = 0.083	Work org	0.750	0.062	0.000
Inconsistency = 0.000				
SYSTEM	Training	0.659	0.275	0.000
Weight = 0.417	Appraisl	0.156	0.065	0.000
Inconsistency = 0.025	Supervis	0.185	0.077	0.000
SKILLS	Range	1.000	0.417	0.000
Weight = 0.417				
Inconsistency = 0.000				
CULTURE	Communic	0.405	0.034	0.000
Weight = 0.083	Coordina	0.481	0.040	0.000
Inconsistency = 0.025	People	0.114	0.009	0.000

[Inconsistency of pairwise comparisons between categories = 0.000]

*Pairwise comparisons with inconsistency values > 0.1 should be redone.

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