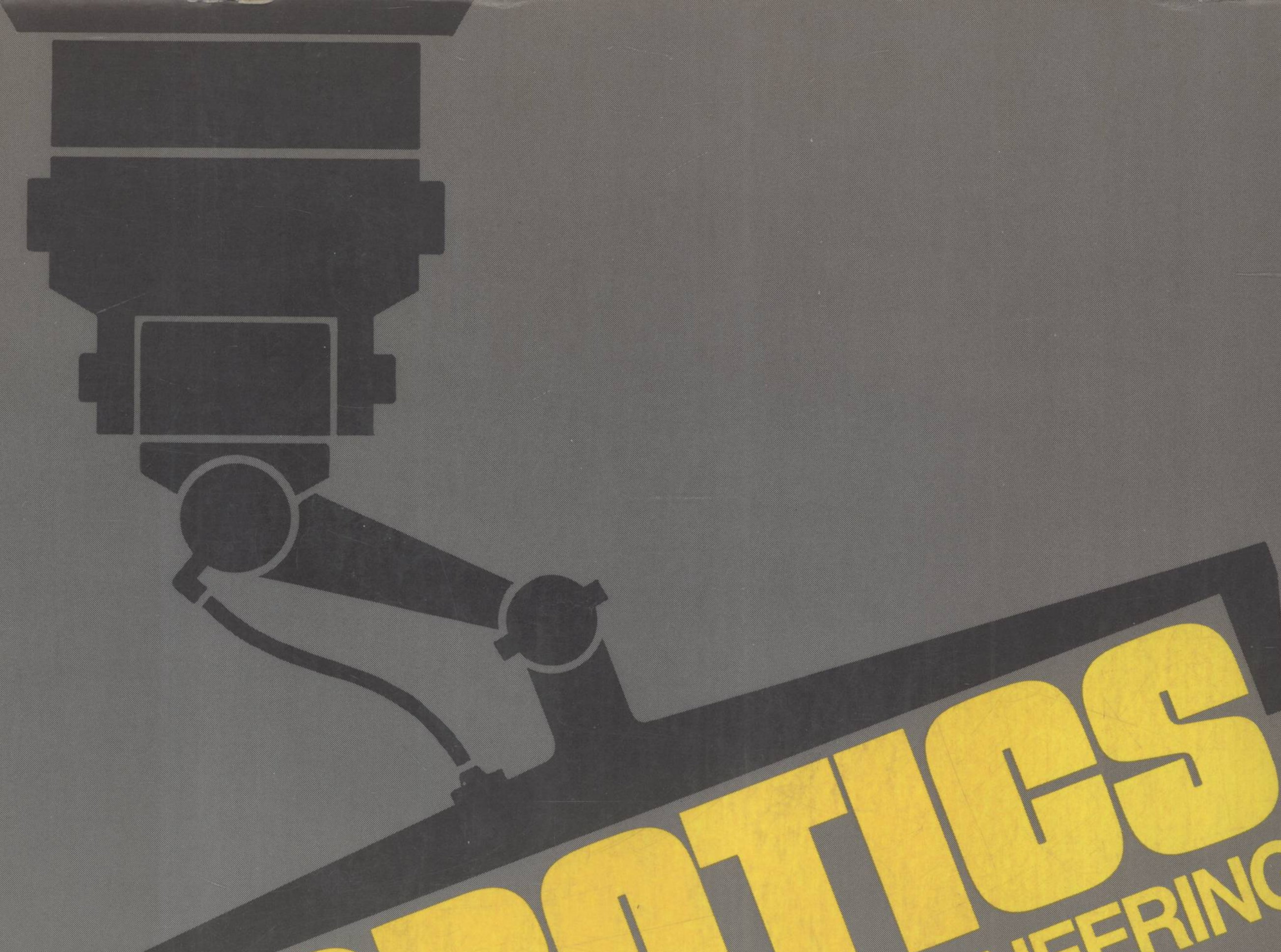

ROBOTICS AND INDUSTRIAL ENGINEERING

SELECTED READINGS

Volume II

Edited by Edward L. Fisher and Oded Z. Maimon

ROBOTICS

AND INDUSTRIAL ENGINEERING: SELECTED READINGS

Volume II

Editors: Edward L. Fisher, Oded Z. Maimon

Published by:
Industrial Engineering and Management Press
Institute of Industrial Engineers

Industrial Engineering and Management Press, 25 Technology Park/Atlanta, Norcross, Georgia 30092

Published 1986
Printed in the United States of America

ISBN 0-89806-082-6

ROBOTICS AND INDUSTRIAL ENGINEERING: SELECTED READINGS
Volume II

PREFACE

The Changing Landscape

Since the publication of the first *Robotics and Industrial Engineering* collection in 1983, a number of interesting changes have taken place in industrial robots. The most noticeable changes are the increased number of robots at work today and the widespread integration of robots with their environments. The latter includes the control of automated systems and increased use of sensory devices for input—robots are becoming more *in touch* with their environments. Force and vision are more prominent as these systems become cost-effective.

It is anticipated that robots will continue to acquire human-like capabilities, including enhanced intelligence. These changes are nowhere more evident than in our updated glossary. Terms that are creeping into the mainstream of robotic literature include artificial intelligence, expert systems, cell control, and distributed processing, all a reflection of an emerging world that emphasizes intelligent and distributed manufacturing computing systems.

Another interesting development is a change in the robotics market. The U.S. market, significantly behind the Japanese at the publication of the first collection, is now the fastest growing with a growth rate of 411% projected between 1985 and 1990. U.S. company robot purchases will actually surpass all other countries by 1990, according to projections.

Robotics and Industrial Engineering

The industrial engineering role is one of analyzing, selecting, implementing, and controlling robotic systems. IEs deal with robotic *systems* rather than stand-alone devices. They view the robot as a component of a *system* where the robot promises to enhance the *system's* productivity. The flexible automation that robots provide allows manufacturing systems to produce multiple products with shorter planning times. Robots allow better consistency in product quality because a task is performed the same way every time and not subject to the daily fluctuations that are experienced by some human-dependent system. Robots also protect people from hazardous practices such as spray painting.

Hardware and software to carry out particular tasks automatically are well developed and already in existence in manufacturing. However, even with adequate automation equipment, manufacturing as a *system* does not usually live up to performance expectations. One main reason for this phenomenon is the lack of appropriate integration and control between the various system components.

The IE must play a primary role in integrating these components. Other roles are in planning, management, and simulation of the manufacturing system. A new technology toolkit is required to solve these emerging problems. Technologies such as artificial intelligence integrated with traditional paradigms will change the way we design and control manufacturing systems dramatically. In a recent survey, upper management indicated a belief that, in the current state of manufacturing, a 27% productivity gain will occur as a result of integration, while only approximately 9% will result from improving separate components. The industrial engineering discipline must respond to the challenge and take advantage of this opportunity to be the *integrators*, otherwise other disciplines will assume this role. As a famous quote by William Shakespeare taken from *As You Like It* proclaims, *All the world is a stage...*, and now is the time for IEs to step into the spotlight and *integrate* that world.

About This Collection

The articles that are contained within these covers provide the reader with a snapshot of new developments in robotics (as they pertain to the IE) since the initial collection. The volume is grouped into the following chapters:

1. Justification of Robotic Technology
2. Selection Criteria
3. Robotic Cell Design
4. Planning and Control of Robot Work Methods
5. Implementation Issues

To facilitate the use of this collection each section above is introduced with a brief summary of its contents, a glossary is provided that includes updated entries from the first collection, and an index allows the reader to efficiently locate topics of interest.

E.L. Fisher, Raleigh
and
O.Z. Maimon, Cambridge

CONTENTS

IV. PLANNING AND CONTROL OF ROBOT WORK METHODS

V. IMPLEMENTATION ISSUES

CHAPTER I: JUSTIFICATION OF ROBOTIC TECHNOLOGY

One of the first tasks to be performed before implementing robots is to determine that there is, in fact, an economic case for implementation. The set of articles in this chapter investigates economic, safety, and environmental issues involved in justifying industrial robots. Included are articles that analyze the economic viability of a robotic implementation and the comparison of robots and humans for the same task.

Reprinted from the 1982 Annual Industrial Engineering Conference Proceedings.

A GENERALIZED METHODOLOGY FOR ASSESSING THE ECONOMIC CONSEQUENCES OF ACQUIRING ROBOTS FOR REPETITIVE OPERATIONS

G. A. Fleischer
University of Southern California

INTRODUCTION

Robot Installations: Substantial and Growing

Beginning with the development in the mid-60's of the microprocessor, which permitted robots to be made smaller and cheaper, and spurred by endemic wage inflation, robots have been used with increasing frequency in the industralized nations. There are differences of opinion as to the number of robots currently in place around the world. One estimate is that there are about 20,000 working industrial robots world-wide, with about 60% of these in the automobile industry [30]. Another estimates about 15,000 robots in the Western industralized nations, with 10,000 in Japan and 3,000 in the U.S. at the end of 1979 [29]. Still another source estimates 40,000-50,000 in worldwide use in 1979, with 30,000 of these installations in Japan [3].

Expert opinion appears unanimous that the forecasted growth of robot installations will be spectacular into the foreseeable future. It is estimated that installations will increase at the rate of 30-35% over the next decade [30]. (The first and largest of the robot manufacturers in the U.S., Unimation, Inc. of Danbury, Connecticut, experienced a 30% per annum growth rate over the past seven years.) Estimates of industry sales potential range from $2 billion to $4 billion by 1990. (In 1980, industry sales in the U.S. were about $100 million [30]). A recent forecast by the Society of Manufacturing Engineers and the University of Michigan estimates that by 1987, 15% of all assembly systems in the U. S. will use robot technology.

There are several significant reasons underlying expectations for substantial growth of robot installations in the foreseeable future. First, the conditions which led users to adopt robots over the past decade will persist, principally with respect to higher wage rates. Second, unit costs can be expected to decrease because robots are becoming smaller and more flexible and new manufacturers are entering the industry. Third, applications will increase as the functional capabilities are expanded, especially with respect to the ability of robots to see properly the articles which they are manipulating.

The Problem

The engineering design aspect of robots is awesome, yet it is the economic aspect which is fundamental to the user's decision to acquire this equipment. After all, robots generally perform no functions which cannot otherwise be performed by combinations of human workers, machines and devices. The decision to acquire robots is influenced, wholly or in part, by the economic consequences to be expected from the decision. A preliminary review of the literature suggests that this issue has received little attention relative to the design and operational characteristics of robots. Certain cost estimates are widely quoted in the literature*, but these are generally inadequate as a guide to prospective users who may be contemplating capital investments of $3,000 to $150,000 per installation. (Multiple installations, i.e., implementation of systems using two or more robots, are not uncommon. Capital investment in the millions of dollars may be required in these instances, of course.)

Large, relatively sophisticated firms will probably have the expertise "in-house" to conduct appropriate economic analyses. However, as robot installations become more extensive, it is likely that smaller, less sophisticated firms will be considering the acquisitions of robots, and they will need competent guidance as to the economic justification for these decisions. It is this issue which underlies the discussion in the following sections.

Objective

There are a variety of ways of describing the process by which prospective users arrive at the decision to acquire a specific robot or robotic system. For our purposes here, we may focus on three principal stages. First, the appropriate decision maker(s) within the firm must focus upon a limited set of candidates from among the much larger population of robots (and related auxiliary

*For example, Unimation Inc. reports that a robot's cost is in the range of $4.00 - $4.60 hourly, and this has remained relatively constant since 1961. (As reported in [17]). This is a rough estimate, however; it is based on straight line depreciation rather than cost of capital recovery, and taxes are ignored.

equipment and software) currently available in the marketplace. (It is assumed, at this point, that the decision maker has already completed an analysis of the task(s) and operating environment and is reasonably convinced that a robot system may represent an optimal solution to the manufacturing* problem). At this stage it will be necessary to describe important technical requirements for the robot(s), including: capacity, drives and controls, memory, and other features such as tactile, feedback and visual sensors. These technical requirements must then be matched against availability. The central feature of this first stage is the identification of a set of candidate systems with technical characteristics suitable to the firm's operational requirements. This includes, in addition to the robots themselves, associated requirements such as changes necessary to other equipment, tooling, spare parts and test equipment for maintenance, utilities, back-up equipment to be used if and when the robot is down, safety equipment, and the like.

The second stage is an economic analysis of the consequences, or impacts, of the candidate robot systems as identified in the first stage. This is the primary focus of this paper in which we explore the development of an evaluation methodology which will permit users to forecast, or assess, the economic consequences of acquiring one or more robots for repetitive operations. Users are assumed to be any business firms (manufacturers, fabricators, processors, etc.) or governmental agencies who may be considering the purchase of robots as operational alternatives and for whom the economic consequences are relevant to the acquisition decision.

*Here, "manufacturing" includes fabrication, assembly, inspection, material handling and other tasks associated with the production of manufactured goods.

The third phase in this process, as illustrated in Exhibit 1, is one in which economic consequences are considered jointly with other (non-economic) consequences so as to arrive at a choice from among alternative systems. There are a variety of approaches to this "multiple criteria"problem, some of which are relatively complex. In any event, this is not an issue which we will address further at this time. Our focus here is only Stage 2, the economic analysis.

CRITERIA FOR A GENERALIZED METHODOLOGY

Prior to developing a generalized methodology for assessing the economic consequences of acquiring robots for repetitive operations, it is necessary to make explicit the criteria by which the efficacy of the methodology will be measured. These same criteria can also be used systematically to critique the existing relevant literature. For our purposes, then, the following criteria will be established:

(1) Theoretically sound -- We are not interested solely in obtaining a solution. The solution must be internally consistent with the decision maker's (user's) objectives as well as the assumptions underlying the model.

(2) Credible -- The user must have a feeling of confidence that the methodology will in fact provide solutions that are useful in the decision making process. The methodology must be believable.

(3) Verifiable -- The user should be able to replicate, or verify, the results by tracing the chain of events from data input to ultimate solution. Verifiability is a precondition to credibility.

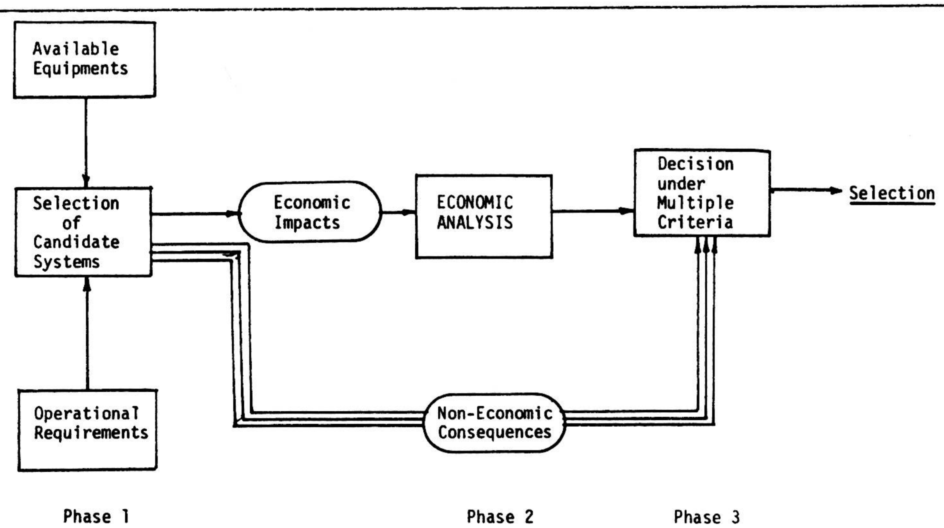

Exhibit 1. A Simplified Schematic Representation of the Decision Process for Acquiring a Robotic System

(4) Comprehensive -- The economic model(s) imbedded in the methodology should include all the economic impacts which can reasonably be expected to occur as the result of the decision. (The time interval over which these impacts will occur is the planning horizon.) Thus the methodology should include the economic consequences of the total system -- equipment acquisition, operation and maintenance, taxes, and the like -- throughout the entire planning horizon. This is the Total System Costs concept.

(5) Reasonable data requirements -- Although comprehensibility is a desirable, if not essential, element of the assessment methodology, it is unrealistic to expect that the analyst will be able to deal exhaustively with absolutely all economic impacts. To do so is neither possible nor desirable. The data requirements for the economic models should be limited to only those which are likely to have a significant affect on the user's capital allocation decision. The cost of gathering impact data and exercising the models should in no case exceed the economic advantage to be gained from the analysis.

(6) Accuracy -- The level of accuracy should not exceed that which is necessary to identify significant differences among alternatives.

(7) Assumptions made explicit -- The assumptions underlying the methodology and imbedded in the analytical models should be stated clearly.

(8) Important factors stressed -- Not all elements of the analysis are of equal importance. Those which have greatest significance should be highlighted.

(9) Uncertainity treated explicitly -- Equipment acquisition decisions are property based upon anticipated consequences expected to result from the various alternative courses of action. These consequences lie in the future, and hence are uncertain. (Some would argue that the more distant the event, the greater is the uncertainty, but this is not necessarily so.) The extent to which this uncertainty affects the decision should be made explicit so that it may be treated by the decision maker as a separable issue.

(10) Incorporated efficiencies over time -- The learning curve (improvement curve, progress curve, etc.) has been used for more than forty years to describe the relationship between productivity (cost/quantity) and time. During the initial stages of production, in particular, productivity is improving as the people and machines in the process "learn" to operate more effectively. Economic models should incorporate this effect.

(11) Reflects real and relative price changes -- Economic impacts should not be expected to remain constant over time, particularly over a long planning horizon. In part, these differences result from changes in the relative prices of specific goods and services, popularly known as inflation. Inasmuch as relative price changes may be of significance to the capital allocation decision, they should be incorporated into the analysis. This is especially important for those goods and services for which prices change at substantially different rates.

LITERATURE REVIEW

During the summer of 1981 an intensive review of the literature was conducted to identify the extent to which published material describing the economics of robotics is available to prospective users. Sources for review included newspapers and popular magazine articles, anthologies (especially W. R. Tanner's Industrial Robots), professional conference proceedings, government reports, and technical papers of professional societies (especially the Society of Manufacturing Engineers). Consultants working in this field were also contacted for leads. More than 200 individual items were reviewed; the references appearing in the Bibliography are representative. Of these, only the dozen listed in Exhibit 2 are directly related to economic analyses of robot installations.

The Accounting Method

As indicated in Exhibit 2 these references may be characterized by one or more of several analytical procedures. The accounting method describes economic consequences (costs and benefits) in accounting terms, that is, the effect of the installation on the firm's income and expense accounts. Thus the cost of capital recovery is defined by annual depreciation expense.*

The principal objection to the accounting method is that the opportunity cost is ignored. The opportunity cost, sometimes described as the minimum

*Allan [3] includes a separate item for "cost of money" in his numerical example. Thus his approach is a combination of the accounting method and discounted cash flow.

		Accounting Method	Payback Method	Discounted Cash Flow
1.	Abraham and Beres, 1978 [1]			X
2.	Allan, 1979 [3]	(x)		(x)
3.	Behuniak, 1979 [4]	X	X	X
4.	Behuniak, 1980 [5]	X	X	X
5.	Bublick, 1979 [6]		X	X
6.	Engelberger, 1979 [9]		X	
7.	Engelgerger, 1980 [10]	X	X	
8.	Ernst, 1980 (?) [11]	X		
9.	Fitch and Bryce, 1981 [14]		X	X
10.	Hanify and Belcher, 1975 [16]			X
11.	Heginbotham, 1977 [18]		X	
12.	Stout, 1973 [32]	X		X
13.	Tanner, 1978 [34]	X	X	X
14.	Weisel, 1975 [38]		X	

Exhibit 2. Publications Related to Economic Analysis of Robot Installations

attractive rate of return, is the return which would be expected from alternative investment opportunities should the specific project proposal not be funded. As described in the literature of engineering economy, the concept of capital recovery (CR) incorporated the opportunity cost as follows:

$$CR = (C-L)(A/P,\ i,\ N) + Li \qquad (1)$$

where C = initial cost

L = net salvage (residual) value at the end of N periods

i = opportunity cost (discount rate)

N = service life of the investment

and (A/P, i, N) = functional form of the algebraic expression

$$= \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (2)$$

It may be shown, in general, that capital recovery does not yield the same results as those derived from the popular depreciation methods. To illustrate, consider straight line depreciation. The annual depreciation expense (D) is given by:

$$D = (C_d - L_d)/N_d \qquad (3)$$

where C_d = cost basis

L_d = expected salvage value for depreciation purposes

N_d = depreciable life

To simplify our example, let us suppose that $C = C_d$, $L = L_d$ and $N = N_d$. It may be shown that the percent error (Δ) is given by

$$\Delta = 1 - \frac{(1-p)/N}{(1-p)(A/P,\ i,\ N) + pi} \qquad (4)$$

where p = L/C

The percent error (Δ) is shown graphically in Exhibit 3 for N = 5. The error increases with the discount rate and the ratio of salvage value to initial cost. When i = 20% and p = 0 (no salvage value), for example, the error is approximately 40%. When i = 20%, and p = 0.50, the error is about 62%.

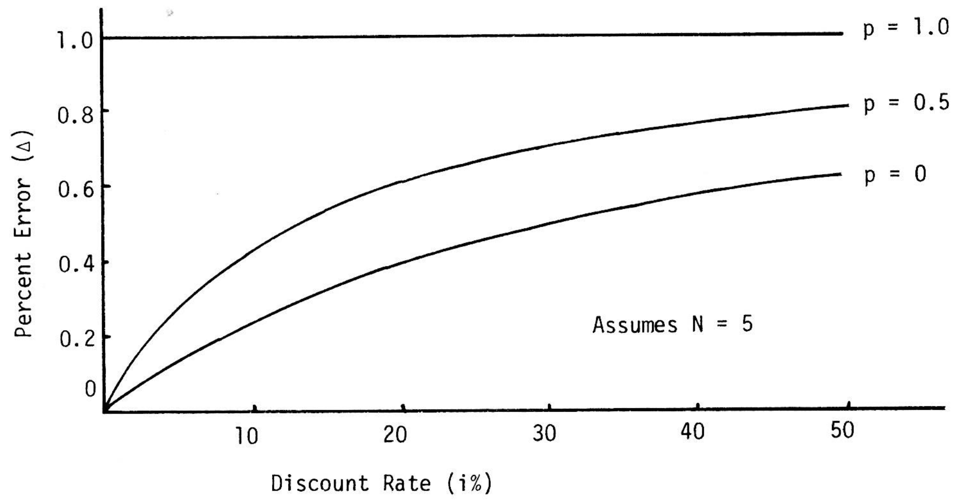

Exhibit 3. Difference Between Capital Recovery and Straight Line Depreciation As a Function of Discount Rate

(Note that D = 0 and CR = i for all values of N when p = 1.00. Thus, in this special case, Δ = 100% for all values of N.)

The Payback Method

As illustrated in Exhibit 4, payback (or payout) is the number of periods required for cummulative benefits to exactly equal cummulative costs. Costs and benefits are usually expressed as cash flows, although discounted present values of cash flows may be used. In either case, the payback method is based on the assumption that the relative merit of a proposed investment is measured by this statistic. The smaller the payback (period), the better the proposal.

Despite the apparent fact that the payback method is widely used in industry, it suffers from serious theoretical dificiencies. The most important of these is that the payback method ignores the consequences of the proposed investment after the period in which payback is completed. This may be shown with reference to Exhibit 5. Here we have two competing projects, Alternatives A and B, with payback for A less than that of B. But it is unlikely that A would be preferred to B since the

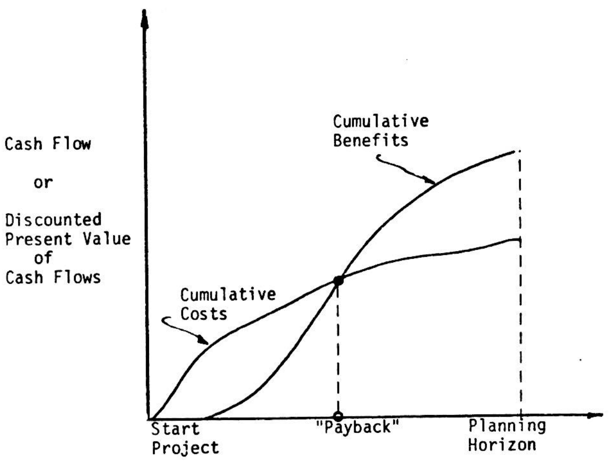

Exhibit 4. Payback (Payout) Illustrated

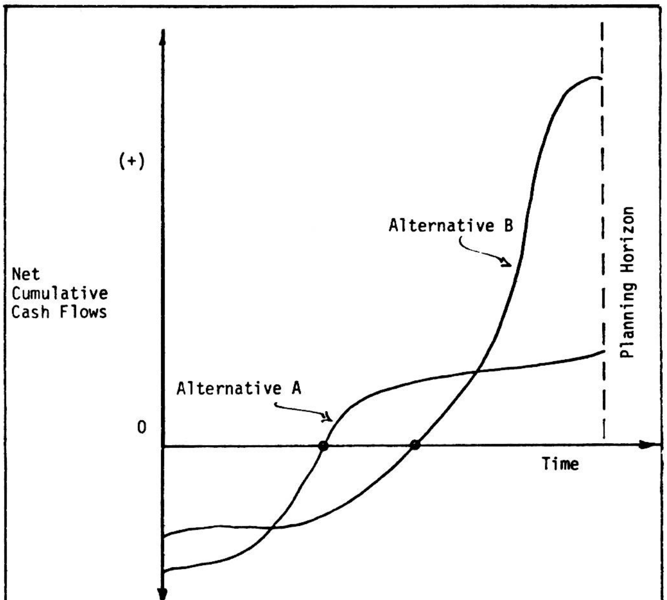

Exhibit 5. Payback for Two Competing Investment Alternative