NIST Advanced Manufacturing Series 200-5

Investment Analysis Methods

A practitioner's guide to understanding the basic principles for investment decisions in manufacturing

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1. Introduction

There are numerous processes, technologies, and capital investments that manufacturers must choose from to produce their goods. New processes are developed and old ones are altered. Firms must decide whether they are going to adopt a new technology/process or maintain their current system. For instance, a manufacturer may need to assess whether a new additive manufacturing system is cost effective or which milling machine is the most cost effective. These decisions can be difficult, especially for smaller firms, as they have fewer resources to expend on researching a potential investment.

1.1. Background

There are many methods that have been developed and used for economic decision making, including net present value, internal rate of return, and payback period. These methods each have their strengths and weaknesses. Some are more intuitive but do not provide sound decision making in all circumstances. Others provide more robust decision making, however, are not very intuitive. Additionally, economic evaluation methods continue to be altered and evaluated in journals such as *The Engineering Economist*. Further, generally accepted accounting methods (e.g., depreciation) do not coincide with good investment decision making.

1.2. Purpose

This guide was assembled to aid manufacturers in evaluating potential investments. It is an overview of the primary methods used for evaluating investments in manufacturing technologies and was designed to minimize the amount of time and resources needed to understand them.

1.3. Scope

The scope of this guide is to provide assistance in making investment decisions regarding investments in capital and processes in manufacturing. It is not a comprehensive review of investment decision making, but rather selects those methods that can be readily applied by non-experts. In addition to presenting methods for decision making, this guide also discusses some risk factors that firms might face when adopting a technology, process, or other investment. For instance, employee resistance to organizational change can turn a seemingly solid investment into a significant loss.

A best practice for investment analysis is to use standardized cost categories. Standard categories allow producers to more readily identify common costs across their operations. It also allows one to compare their costs across firms or to national data. Additionally, there might be costs that a manufacturer cannot estimate and might need to approximate using industry wide data. These situations require standardized cost categories. An appendix discusses the common categorization of costs in the US that a manufacturer might need for an investment analysis.

Section 2 presents well-established methods for making investment decisions, which include net present value and the internal rate of return. These methods can be supplemented with the approaches presented in Section 3. Challenges posed by organizational change is discussed in Section 4 and standard methods for categorizing costs is presented in Appendix A.

2. Prominent Methods for Economic Evaluation

An article by Graham and Harvey provides some insight into the more prominent methods for investment analysis.[1] They surveyed 392 chief financial officers (CFO) about the cost of capital, capital budgeting, and capital structure. Surveys were sent to CFO's for firms listed in the Fortune 500 rankings. Approximately 40 % of the firms were manufacturers and another 15 % were financial. Respondents were asked on a scale from 0 to 4, "how Frequently does your Firm use the Following Techniques when Deciding which Projects or Acquisitions to Pursue." It listed 11 techniques with 0 representing "never use it" and 4 meaning "always use it." The results are provided in Table 2-1. The first column in the table describes the method while the second column provides the percent who responded with 3 or 4. The third column is the average response. The fourth and fifth columns provide the average response of small firms and large firms. The most prominent method used in economic decision making seems to be the internal rate of return. The survey revealed that 75.61 % of respondents always or almost always use this method when making investment decision, as seen in the second column of Table 2-1. As seen in the fourth and fifth columns, small firms had lower responses for internal rate of return and net present value, which are considered by finance experts to be best practices.

Although it has some limitations, internal rate of return, which, according to Table 2-1, is used the most, is a very intuitive method of analysis, as most people are familiar with estimating a rate of return. As seen in the table, the second most used is net present value and is considered the most accurate for decision making, as presented in most finance text books. Both of these approaches are discussed in this chapter. These approaches require an understanding of discount rates and adjusting for inflation; which are discussed in Section 2.1 and Section 2.2. Section 3 discusses some of the other approaches for investment analysis, which are typically considered to be supplements to net present value and the internal rate of return. Three approaches listed in Table 2-1 are not discussed in this document: value-at-risk, earnings multiple approach, and accounting rate of return. These approaches are not discussed as they tend to be less applicable to individual project decisions for the target audience of this report.

Each of the methods discussed in this report are applicable to certain decision types and have some limitations. Nearly all of the methods can be used in an accept/reject decision for an investment, as seen in Table 2-2. A selection of them can be used for making decisions regarding design and size of a project while fewer can be used to prioritize or rank investments. An example of the different types of investment decisions are shown in Table 2-3. A number of limitations and considerations apply to each of the methods, as seen in Table 2-4. Many of the approaches require an examination over the same study period or assuming that assets can be expected to repeat the cost/benefits of the original investment, as these methods do not consider information about the duration of a project.

[1] Graham, John and Campbell Harvey. "The Theory and Practice of Corporate Finance: Evidence from the Field." Journal of Financial Economics 60 (2001): 187-243.

Table 2-1: Survey Response to "How Frequently does your Firm use the Following Techniques when Deciding which Projects or Acquisitions to Pursue"

	% always or almost always	Average Response#	Average Response by Firm Size# Small	Large
Internal Rate of Return	75.61	3.09	2.87	3.41***
Net Present Value	74.93	3.08	2.83	3.42***
Payback Period	56.74	2.53	2.72	2.25***
Hurdle Rate	56.94	2.48	2.13	2.95***
Sensitivity Analysis	51.54	2.31	2.13	2.56***
Earnings Multiple Approach	38.92	1.89	1.79	2.01*
Discounted Payback Period	29.45	1.56	1.58	1.55
We incorporate the "real options" of a project when evaluating it	26.59	1.47	1.4	1.57
Accounting Rate of Return	20.29	1.34	1.41	1.25
Value-at-Risk or other Simulation	13.66	0.95	0.76	1.22***
Adjusted Present Value	10.78	0.85	0.93	0.72
Profitability Index	11.87	0.83	0.88	0.75

* Statistically Different at the 1 % level
** Statistically different at the 5 % level
*** Statistically different at the 10 % level
\# Respondents were asked on a scale from 0 (never use) to 4 (always use)
Source: Adapted from Graham, John and Campbell Harvey. "The Theory and Practice of Corporate Finance: Evidence from the Field." Journal of Financial Economics 60 (2001): 187-243.

2.1. Discount Rate

A discount rate is sometimes referred to as a *hurdle rate*, interest rate, cutoff rate, benchmark, or the cost of capital.[2, 3] Many firms have a fixed discount rate for all projects; however, if a project has a higher level of risk, one should use a higher discount rate commensurate with that risk. This is similar to loaning money to someone who has an elevated likelihood of not paying the loan back. Typically, this person is charged a higher interest rate. Selecting a discount rate is, for many, a challenge. It is, typically, greater than or equal to the return on other readily available investment opportunities (e.g., stocks and bonds). It is, essentially, the minimum rate of return that one would need to engage in a particular investment (e.g., 10 % annual return, 12 % annual return, or higher). One method for selecting a discount rate is the weighted-average cost of capital, which is discussed by Brealey et al.[4] If there is uncertainty about selecting a rate, one might also use a range for a discount rate (e.g., 9 % to 12 %) and calculate two or more estimates for the net present value or conduct a Monte Carlo simulation as discussed in

[2] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Methods for Investment Analysis. Baltimore, MD: United Book Press, Inc, 2001. 2.
[3] Brealey, Richard and Stewart Myers. Principles of Corporate Finance. 6th ed. New York, NY: McGraw-Hill, 2000. 17.
[4] Brealey, Richard, Stewart Myers, and Franklin Allen. Principles of Corporate Finance. 11th ed. New York, NY: McGraw-Hill, 2014.

Table 2-2: Application of Methods for Investment Analysis

	Net Present Value	Adjusted Present Value	Internal Rate of Return	Modified Internal Rate of Return	Payback Period and Discounted Payback Period	Profitability Index	Monte Carlo Analysis	Decision Trees
Accept/Reject	X	X	X	X	X[1]	X		
Design	X	X	X[2]	X[2]		X[2]		
Size	X	X	X[2]	X[2]		X[2]		
Priority or Ranking			X	X		X		
Uncertainty and potential outcomes							X	X

1: Note significant limitations

2: Appropriate when incremental discounted costs and benefits are considered (i.e., the difference in costs/benefits between two investments). To decide between more than two options, pairwise comparisons are necessary.

Table 2-3: Examples of Manufacturing Industry Investment Decisions

Accept/Reject	- Is an additive manufacturing system cost effective? - Is a new HVAC control system cost effective? - Is a new robotic system cost effective?
Design	- What robotic system is the most cost effective? - What HVAC control system is the most cost effective? - Which milling machine is the most cost effective? - Is it more cost effective to use steel or aluminum materials?
Size	- How many machine tools should be replaced? - What size of lathe is most cost effective?
Priority or Ranking	- Is it more cost effective to invest in new machine tools or a new HVAC control system? - We have five proposed investments but can only afford a selection of them. Which investments do we choose?
Uncertainty and potential outcomes	- We are considering an investment in using aluminum in place of steel for our product. We need to consider potential customer responses. - We are considering the adoption of a new process; however, the response of employees will determine the cost effectiveness of the investment. We need to consider multiple outcomes. - We are considering the installation of solar panels; however, the cost effectiveness depends on the weather. We need to consider variations in weather conditions.

Table 2-4: Limitations and Considerations of Methods for Investment Analysis

Method	Limitation
Net Present Value	Alternatives must be compared over the same study period.
Adjusted Present Value	Alternatives must be compared over the same study period.
Internal Rate of Return	In some instances, inconsistent results may arise. This calculation does not reveal information about the size or duration of a project. Alternatives must be compared over the same study period or it must be assumed that assets can be expected to repeat the costs/benefits of the original investment.
Modified Internal Rate of Return	This calculation does not reveal information about the size or duration of a project. Alternatives must be compared over the same study period or it must be assumed that assets can be expected to repeat the costs/benefits of the original investment.
Payback Period and Discounted Payback Period	Cash flows beyond the payback period are ignored. Projects selected on this criterion may not be cost effective.
Profitability Index	This calculation does not reveal information about the size or duration of a project. Alternatives must be compared over the same study period or it must be assumed that assets can be expected to repeat the costs/benefits of the original investment.

Section 3.1. When adopting a new technology, one might consider the barriers to adoption that lead to investment risk. Some potential barriers are discussed in Section 4.

2.2. Adjusting for Inflation

Some costs increase over time. For example, household energy costs increased 7.9 % between 2006 and 2016. The change in prices is tracked by the Bureau of Labor Statistics and provided to the public in two forms: consumer price index and the producer price index. The consumer price index is a "measure of the average change over time in the prices paid by urban consumers for a market basket of consumer goods and services."[5] The BLS provides estimates for individual categories (e.g., energy) and an average for all goods. The producer price index is a "family of indexes that measures the average change over time in the selling prices received by domestic producers of goods and services."[6] Thus, the consumer price index is more appropriate for estimating the increase in the cost of goods while the producer price index is more appropriate for estimating the revenue received for a good. Both are provided as an index with a base year equaling 100 allowing one to estimate the increase in price between any two years. For example, the

[5] Bureau of Labor Statistics. Consumer Price Index. https://www.bls.gov/cpi/
[6] Bureau of Labor Statistics. Producer Price Index. https://www.bls.gov/ppi/

consumer price index for household energy went from 189.286 in 2010 to 193.648 in 2011, which amounts to a 2.2 % increase:

$$2.2\ \% = \left[\left(\frac{193.648}{189.286}\right) - 1\right] * 100\%$$

This value provides some estimate of the increase in prices that might be expected in the future.

2.3. Present Value

A critical concept for evaluating an investment decision is the time value of money; that is, the relationship between cash flows occurring at different time periods. For example, receiving $1000 today is typically preferred to receiving $1000 one year from now. In order to compare these two cash flows occurring at different dates, the future cash flow is *discounted* to equate its value to cash flows received today.[7, 8] This is done by dividing the future cash flow by an interest rate or discount rate:

Equation 1

$$PV_1 = \frac{CF_1}{1 + r}$$

Where
PV_1 = Present value of future cash flow after one year
CF_1 = Cash flow after one year
r = Discount rate which is, typically, between 0 and 1

The discount rate can be illustrated by considering how much one would need to be compensated to loan $1000 to someone for one year. If that value is $100, then the interest rate is 10 %, which is the discount rate. The $1100 dollars that would be received in one year is equivalent to $1000 today when discounted using Equation 1 and the 10 % discount rate.

To calculate present value for cash flows after multiple years, the numerator in Equation 1 is raised to the power of the number of years that have passed:

Equation 2

$$PV_t = \frac{CF_t}{(1 + r)^t}$$

[7] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 61.
[8] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Investment Analysis. Hoboken, NJ: John Wiley and Sons, 2015. 2-3.

Where
PV_t = Present value of future cash flow after number of t years
CF_t = Cash flow in year t
r = Discount rate which is, typically, between 0 and 1

2.4. Net Present Value

Net present value is the difference between the present value of all cash inflows and the present value of all cash outflows over the period of the investment.[9, 10, 11] Net present value, which accounts for the time value of money, is a common metric for examining an investment, and is considered a superior method over other approaches.[12, 13] Other approaches often have caveats, do not consider all cash flows, or do not consider the time value of money. Net present value is calculated by taking each monetary cost and benefit associated with an investment and adjusting it to a common time period, which we will call time zero. The adjustment is for the time value of money, as described above. In addition to the time value of money, there is also the decreased purchase power of money due to inflation. The inflows are summed together and the outflows (costs) are subtracted resulting in the net present value:

Equation 3

$$NPV = -C_0 + I_0 + \frac{-C_1}{(1+r)} + \frac{I_1}{(1+r)} + \frac{-C_2}{(1+r)^2} + \frac{I_2}{(1+r)^2} \cdots \frac{-C_T}{(1+r)^T} + \frac{I_T}{(1+r)^T}$$

Where:

I_t = Total cash inflow in time period t
C_t = Total cost in time period t
r = Discount rate
t = Time period, which is typically measured in years

Or, written another way

Equation 4

---

9 Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Methods for Investment Analysis. Baltimore, MD: United Book Press, Inc, 2001. 54-56
10 Budnick, Frank. Applied Mathematics for Business, Economics, and the Social Sciences. New York, NY: McGraw-Hill, 1988. 894-895.
11 Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Investment Analysis. Hoboken, NJ: John Wiley and Sons, 2015. 44-45.
12 Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 223.
13 Helfert, Erich A. Financial Analysis: Tools and Techniques: A Guide for Managers. New York, NY: McGraw Hill, 2001. 235.

$$NPV = \sum_{t=0}^{T} \frac{(I_t - C_t)}{(1+r)^t}$$

The net cash inflows for each time period are divided by one plus a selected discount rate raised to the power of the time period, *t*. One challenge with net present value is determining a discount rate, which was discussed previously. One can select either a nominal or real discount rate, which is determined by whether it is a current or constant dollar analysis. In a current dollar analysis, the costs and benefits are not adjusted for inflation; thus, the discount rate tends to be *higher*. In a constant dollar analysis, the costs and benefits are adjusted to a common year for inflation; therefore, the discount rate is *lower*, as it does not need to account for inflation.

New technologies offer different benefits, including reduced costs or increased revenue. In order to estimate the net present value, it might be necessary to forecast any increased sales to estimate additional revenue due to adopting a new technology. It is important to also include the associated additional costs of production, but only include those costs and benefits associated with the investment. Including costs that would be incurred without the investment in the new technology will negatively skew some of the other measures discussed below.

Interpreting net present value is at times difficult. If net present value is positive, it means that the return on the investment is expected to exceed the discount rate. An anticipated follow-up question is what the rate of return is on the investment. Net present value does not reveal this information. The internal rate of return is more appropriate for answering this question and is discussed in Section 2.5. The net present value, however, can be used to determine whether an investment is economical and to rank investments.

It is important to remember that prices of some goods can change over time at rates different than general inflation. Price escalation occurs when prices increase faster than inflation, while price de-escalation occurs when prices increase slower than inflation (or decline). If an investment has a recurring cost that escalates, then the analysis will need to account for this by having higher cost values for each subsequent time period.

2.5. Internal Rate of Return

Internal rate of return is a widely-used metric for evaluating investments. It has been suggested that in some industries, it is the principal method used for such analyses. The internal rate of return is, essentially, the discount rate at which the net present value is zero. Thus, it is calculated by setting NPV in Equation 4 to equal zero and solving for *r*.[14, 15] Due to the nature of this calculation, individuals use software or trial and error to

[14] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 152-153.
[15] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Methods for Investment Analysis. Baltimore, MD: United Book Press, Inc, 2001. 44-49

identify the internal rate of return (i.e., select varying discount rates for Equation 4 in order to identify the value where the net present value equals zero).

One of the benefits of using the internal rate of return is that there is no need to select a discount rate. Generally, if the internal rate of return is calculated to be greater than or equal to your minimum required rate of return to make an investment (e.g., discount rate or hurdle rate), then the investment is economic.

Unfortunately, the internal rate of return has some deficiencies. The measure does not reveal the size of the investment. For instance, consider a $1 investment opportunity that has a return of 100 % after one year compared to a $10 000 investment that has a return of 30 % after one year. The first opportunity has a higher rate of return while the second one has a higher dollar return. Net present value reveals this difference while the internal rate of return does not.

The internal rate of return also does not reveal the duration of the investment. It is often preferred to have a long-term investment rather than a short-term investment, all else equal, as it avoids the cost and risk of having to reinvest. After a short-term investment is completed, one has to identify the next investment, which may or may not have a high return. Another challenge occurs when a project generates immediate inflows.[16] For instance, consider an investment that has an initial cost of $1000 and generates $1200 after the first year compared to one that immediately generates $1000 and has a cost of $1200 after the first year. Both have an internal rate of return of 20 %; however, using a 5 % discount rate, the net present value of the first case is $143 whereas the second one is $-143. In this instance, the net present value is the better choice for analysis.

Another situation where the internal rate of return is not a sufficient metric can occur when net cash flows for different time periods flip signs. Consider an example provided by Ross where the initial net cash flow is $-100, $230 after the first year, and $-132 in the third year.[17] There are two internal rates of return with one being 10 % and the other 20 %.[18] In this instance, one must use the net present value to make a sound decision. Moreover, the internal rate of return may be an intuitive metric; however, it should be used along with net present value rather than in place of it.

[16] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 152-153.
[17] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 146-149.
[18] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 152-153.

3. Common Supplements for Economic Decision Making

Although net present value is considered the superior measure for economic decision making, there are several supplemental measures that are frequently used. Many of them include net present value or are variants of it. These different supplements are discussed below.

3.1. Sensitivity Analysis with Monte Carlo Techniques

To account for uncertainty, a probabilistic sensitivity analysis can be conducted using Monte Carlo methods. This technique is based on works by McKay, Conover, and Beckman[19] and by Harris[20] that involves a method of model sampling. It can be implemented using various software packages such as the Crystal Ball software product[21] or the Cost Effectiveness Tool provided by NIST.

Specification involves defining which variables are to be simulated, the distribution of each of these variables, and the number of iterations performed. The software then randomly samples from the probabilities for each input variable of interest. Three common distributions that are used include triangular, normal, and uniform. To illustrate, consider a situation where a firm has to purchase 100 ball bearings at $10 each; however, the price can vary plus or minus $2. In order to address this situation, one can use a Monte Carlo analysis where the price is varied using a triangular distribution with $12 being the maximum, $8 being the minimum, and $10 being the most likely. Moreover, the anticipated results should have a low value of approximately $800 (i.e., 100 ball bearings at $8 each) and a high value of approximately $1200 (i.e., 100 ball bearings at $12 each). The triangular distribution would make it so the $8 price and $12 price have lower likelihoods.

For a Monte Carlo analysis, one also must select the number of iterations that the simulation will run. Each iteration is similar to rolling a pair of dice, albeit, with the probabilities having been altered. In this case, the dice determine the price of the bearings. The number of iterations is the number of times this simulation is calculated. For this example, ten thousand iterations were selected and a simulation was ran using Oracle's Crystal Ball software. The frequency graph shown in Figure 3.1 shows the number of times each value was created. Since a triangular distribution was selected, the far left and far right values are less likely to be selected while the most likely value is in the middle at approximately $1000 (i.e., 100 bearings at $10 each). The sum of all the bars in the graph is a probability of 1.0 with a total frequency of 10 000. Instead of a triangular distribution, a uniform distribution could have been selected where each value

[19] McKay, M. C., Conover, W. H., and Beckman, R.J. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," Technometrics 21 (1979): 239-245.
[20] Harris, C. M. Issues in Sensitivity and Statistical Analysis of Large-Scale, Computer-Based Models, NBS GCR 84-466, Gaithersburg, MD: National Bureau of Standards, 1984.
[21] Oracle. Crystal Ball, Crystal Ball 11.1.2.3 User Manual. Denver, CO: Decisioneering, Inc, 2013.

between $8 and $12 has an equal chance of being selected in each iteration. The results from such a distribution are shown in Figure 3.2.

The benefit of Monte Carlo analysis is in the situation where there are many variables that can fluctuate (e.g., price of energy, materials, and labor). Instead of having just one price fluctuating, maybe a dozen prices fluctuate.

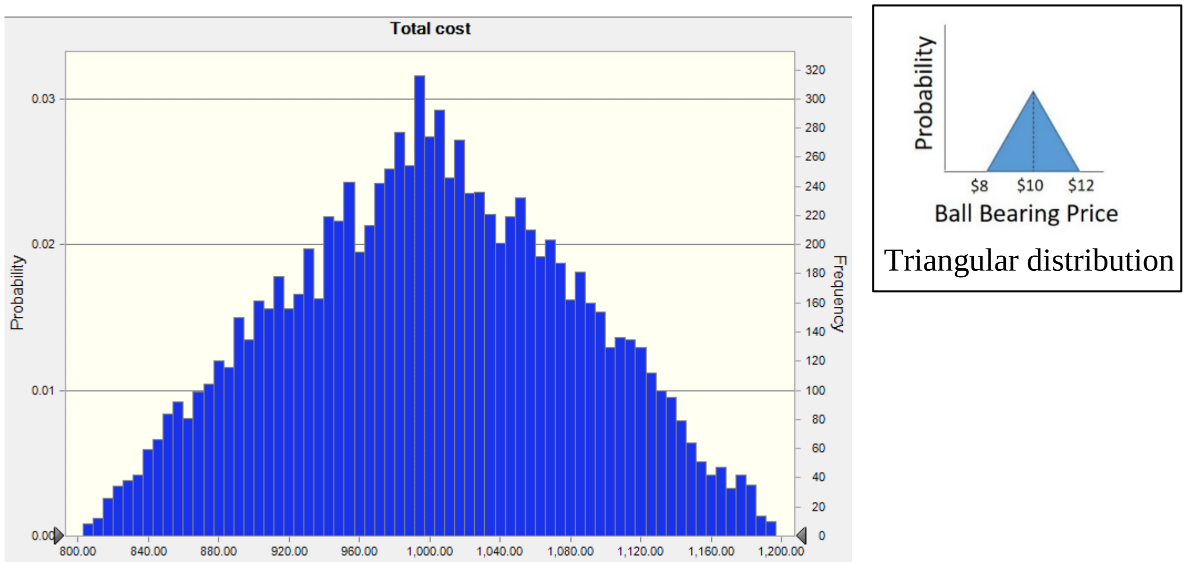

Figure 3.1: Frequency Graph of the Total Cost for Ball Bearing Example using a Triangular Distribution

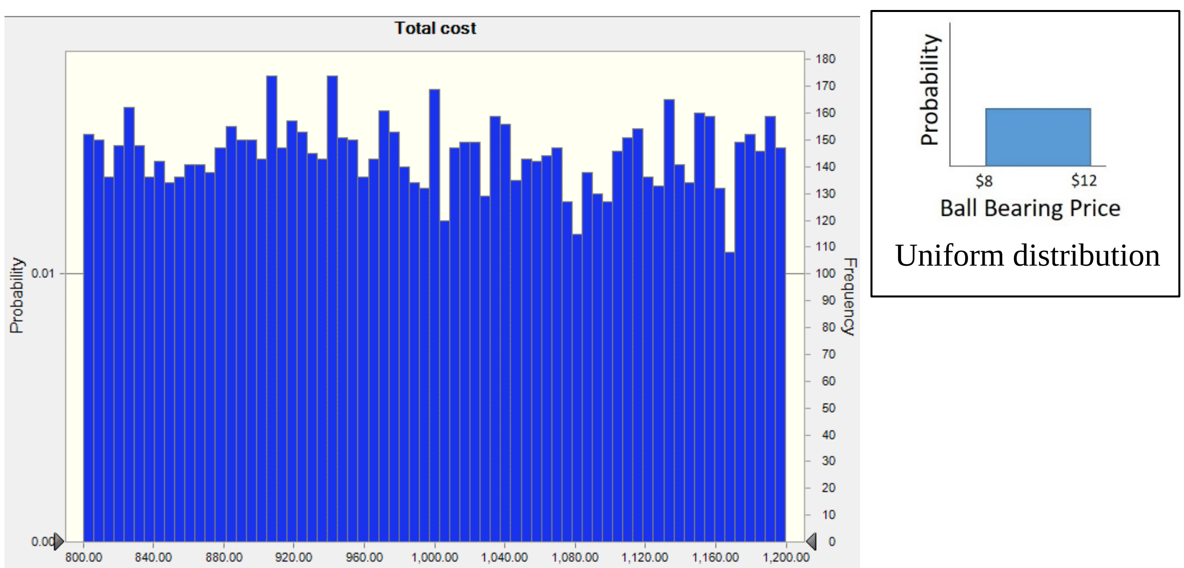

Figure 3.2: Frequency Graph of the Total Cost for Ball Bearing Example using a Uniform Distribution

3.2. Modified Internal Rate of Return

The modified internal rate of return may or may not be a prominent method used for economic decision making; however, given the prominence of the internal rate of return and the many short comings of this metric, it is prudent to discuss the modified internal rate of return. This calculation assumes that cash inflows are reinvested at the rate of return equal to the discount rate.[22, 23] It can be represented as:

Equation 5

$$MIRR = \sqrt[T]{\frac{\sum_{t=0}^{T}[I_t(1+r)^{T-t}]}{\sum_{t=0}^{T}[C_t/(1+r)^t]}} - 1$$

Where
I_t = Total cash inflow in time period t
C_t = Total cost in time period t
r = Discount rate
t = Time period, which is typically measured in years

This equation is somewhat more complex than the calculation of the internal rate of return, but it avoids many of the downfalls associated with it. As previously mentioned, it is assumed that cash inflows are reinvested, which is why cash inflow I_t is multiplied by $(1+r)^{T-t}$. The cost C_t in the denominator is discounted in a similar fashion to net present value. Moreover, it is the future value of all net incomes divided by the present value of all net costs. The *T* root of this value, less one, is equal to the modified internal rate of return.

3.3. Payback Period and Discounted Payback Period

Payback period is the time required to recoup the investment without discounting any cash flows.[24] For example, consider an investment that has an initial cost of $25 000 with a net cash inflow of $10 000 after one year, $15 000 after two years, and $12 000 after three years. The payback period is two years, as the sum of $10 000 and $15 000 equals the initial investment of $25 000. The discounted payback period makes the same estimation except the cash flows are discounted.[25] Using the previously mentioned example along with a 10 % discount rate, the payback period would be 3 years or less depending on when the cash flows are received during the year.

[22] Lin, Steven. "The Modified Internal Rate of Return and Investment Criterion." *The Engineering Economist.* 1976. 21(4) 237-247.
[23]
[24] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 146-149.
[25] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 146-149.

Payback period and the discounted payback period are often used for small investment decisions. For example, replacing a conference room's lights with energy efficient bulbs or tuning up a vehicle to save fuel. It is a quick method; however, it has a number of significant drawbacks with one being that it does not consider any future cash flows beyond the payback period. For large investments, this method should be considered a supplement to net present value.

3.4. Real Options and Decision Trees

As discussed in Section 2.4, net present value is considered a superior method over other approaches; however, this method does not consider the possibility of adjusting an investment after it has been initiated. A survey presented by Block indicates that 14 % of Fortune 1000 companies used real options in their economic evaluations.[26] Adjusting for decisions, known as real options, can provide additional value to a project.[27] For instance, if a pilot or prototype product is successful, then there is the option to expand. There is also the option to abandon it in the case that it is not successful. Another example can be found in comparing two projects with the same net present value. Consider a project that commits to a technology that cannot be changed for many years compared to one with the same net present value, but there is no commitment to any particular technology. The second project is preferred over the first, as it allows for options. Moreover, real options suggests that the total value of a project is the net present value plus the value of options:

Equation 6

$$TPV = NPV + VO$$

Where
TPV = Total project value
NPV = Net present value from Equation 3 and Equation 4
VO = Value of options

A great deal of the literature on real options focuses on well-defined financial options, which do not always transfer well into project investment.[28] Options pricing theory is an advanced topic, which is not completely covered in this document. For more information, one might consult Copeland and Antikarov or Brealey and Meyers.[29, 30]

[26] Block, Stanley. "Are Real Options; Actually Used in the Real World?" The Engineering Economist. 2007 52(3) 255-267.
[27] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 223.
[28] Van Putten, Alexander and Ian MacMillan. "Making Real Options Really Work." Harvard Business Review. December 2004. https://hbr.org/2004/12/making-real-options-really-work
[29] Brealey, Richard and Stewart Myers. Principles of Corporate Finance. 6th ed. New York, NY: McGraw-Hill, 2000. 583-666
[30] Copeland, Tom and Vladimir Antikarov. Real Options: A Practitioner's Guide. United Kingdom: Thompson Corporation, 2003.

Although real options pricing is not fully discussed here, it can be described in a decision tree. There are, typically, three types of nodes in a decision tree:

Decision nodes represented by squares,
Chance nodes represented by circles, and
End nodes represented by triangles

An example is provided in Figure 3.3, which presents an investment with an initial cost of $15 million. It has a probability of 0.8 that it results in $5 million cash inflow after one

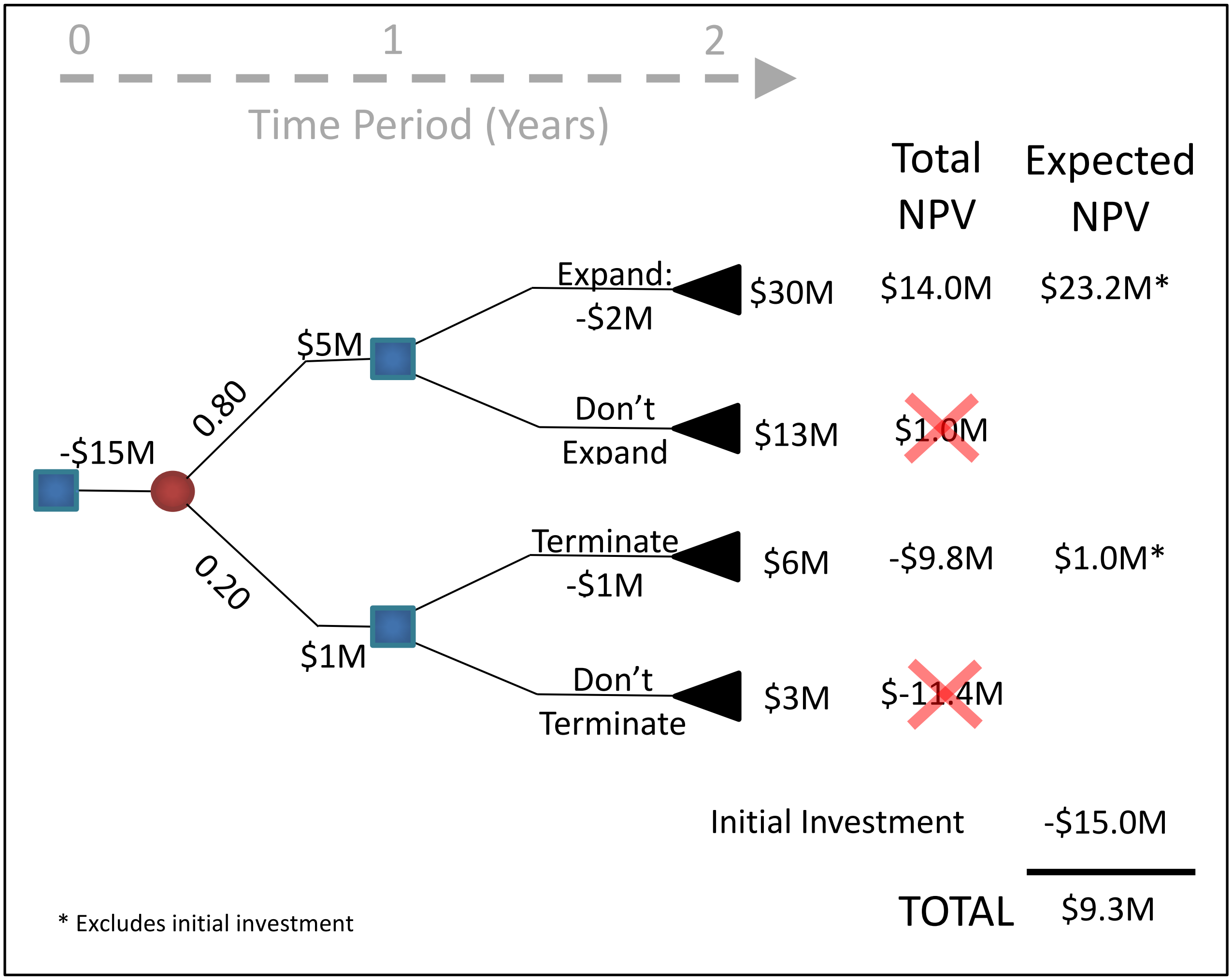

Figure 3.3: Example of a Decision Tree using a 7 % Discount Rate

year and has the option to expand at a cost of $2 million, resulting in an additional $30 million cash inflow in after two years. Alternatively, there is a 0.2 probability of a cash inflow of $1 million with the option to terminate the project at a cost of $1 million, resulting in an additional cash inflow of $6 million in year two. This investment has four possible net present values, as seen in Figure 3.3. Since an investor would choose the highest net present value, we can eliminate those options that would not be chosen (i.e., the second and fourth net present values). We can then calculate the expected net present value by calculating the net present value for the branch with the probability of 0.8 which is

$$\frac{\$5\ million}{1.07} - \frac{\$2\ million}{1.07^2} + \frac{\$30\ million}{1.07^2} = \$29.0\ million$$

We can then calculate the expected net present value for the branch with the probability of 0.2, which is

$$\frac{\$1\ million}{1.07} - \frac{\$1\ million}{1.07^2} + \frac{\$6\ million}{1.07^2} = \$5.2\ million$$

Finally, we can multiply these by their respective probabilities and add the initial cost:

$$0.8 * \$29.0\ million + 0.2 * \$5.2\ million - \$15\ million = \$9.3\ million$$

The expected value of the investment without the options (i.e., no option to expand and no option to terminate) is -\$1.5 million; thus, the options add \$10.7 million to the net present value of the investment (i.e., the difference between \$9.3 million and -\$1.5 million before rounding).

Rather than calculating the expected value, one might use a Monte Carlo analysis, as described in Section 3.1. This is particularly useful in the event that there are multiple chance nodes.

3.5. Adjusted Present Value

Adjusted present value is described as the net present value plus the net present value of financing and the effects of financing.[31] This includes subsidies to debt, cost of issuing new securities, cost of financial distress, or other costs/benefits of financing. It is, generally, assumed that financing occurs solely through equity:

Equation 7

$$APV = NPV + EF$$

Where
APV = Adjusted present value
NPV = Net present value from Equation 3 and Equation 4
EF = Effects of financing (e.g., interest on a loan)

An example of the effects of financing might include a company that, in order to invest, has to issue stock, where doing so comes with costs for underwriting, lawyers, and others involved in the transaction.

[31] Brealey, Richard and Stewart Myers. Principles of Corporate Finance. 6th ed. New York, NY: McGraw-Hill, 2000. 555-557.

3.6. Profitability Index

The profitability index provides a means for ranking competing projects. According to Graham, it is used by approximately 12 % of those surveyed (see Table 2-1).[32] It is the net present value of the cash flows occurring in time periods after the investment divided by the initial net cash flows (e.g., initial investment)[33]:

Equation 8

$$PI = \frac{NPV - (I_0 - C_0)}{(I_0 - C_0)}$$

Where:
PI = Profitability index
I_t = Total cash inflow in time period t
C_t = Total cost in time period t

For example, consider an investment with an initial cost of \$1000 with cash inflows of \$750 after the first year and \$850 after the second year. Using an 8 % discount rate, the profitability index is calculated by summing the discounted future cash flows (i.e., the \$750 and \$850) and dividing it by the initial cash flows:

$$\frac{(\$750/1.08) + (\$850/1.08^2)}{\$1000} = 1.42$$

If the profitability index is greater than one, then, generally, the investment is considered economical. Higher values tend to be better investments. The usefulness of this method is for comparing projects in the case of capital rationing (i.e., the case where there are limited funds for project investment); however, it does not provide sound decision making in the case of capital rationing over multiple time periods. The profitability index, like the internal rate of return, also does not reveal the size of a project. These different drawbacks illustrate that caution should be exercised when using the profitability index.[34] Similar to the payback method, the profitability index should be considered a supplement to net present value.

[32] Graham, John and Campbell Harvey. "The Theory and Practice of Corporate Finance: Evidence from the Field." Journal of Financial Economics 60 (2001): 187-243.
[33] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 164-166.
[34] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 164-166.

4. Unanticipated Investment Costs

When implementing some investments, there are frequently unexpected costs beyond demand and price fluctuations that can impact cash flows; therefore, it is prudent to examine some of the common areas where challenges might arise. For example, a new technology may not be compatible with a firm's current infrastructure or a firm may find that its staff resist the adoption of a technology. The result may be costs that are higher than expected or benefits that are lower than expected. These risks might emphasize the need for a sensitivity analysis using Monte Carlo techniques or utilizing decision trees. This section is not a guide to addressing these challenges, but rather raises the point that there are often unanticipated challenges for some investments. If one is going to conduct an accurate investment analysis, then these items need to be considered. A failure to do so may result in an inaccurate investment analysis where costs are underestimated and/or benefits are overestimated. The following is a brief discussion regarding the capabilities of a firm and organizational change as they relate to an investment.

4.1. Capabilities of a Firm

To create products and services, a firm needs resources, established processes, and capabilities.[35] Resources include natural resources, labor, and other items needed for production. A firm must have access to resources to produce goods and services. The firm must also have processes in place that transform resources into products and services. Two firms may have the same resources and processes in place; however, their products may not be equivalent due to quality, performance, or cost of the product or service. This difference is due to the capabilities of the firm; that is, capabilities are the firm's ability to produce a good or service effectively. Kim and Park present three entities of capabilities (see Figure 4.1): controllability, flexibility, and integration.[36]

Controllability is the firm's ability to control its processes. The objective of controllability is to achieve efficiency that minimizes cost and maximizes accuracy and productivity. Flexibility is the firm's ability to deal with internal and external uncertainties. It includes reacting to changing circumstances while sustaining few impacts in time, cost, or performance. According to Kim and Park, there is a tradeoff between controllability and flexibility; that is, in the short term, a firm chooses combinations of flexibility and controllability, sacrificing one for the other as illustrated at the bottom of Figure 4.1. Over time, a firm can integrate and increase both flexibility and controllability through technology or knowledge advancement among other things.

In addition to the entities of capabilities, there are categories of capabilities or a chain of capabilities, which include basic capabilities, process-level capabilities, system-level capabilities, and performance. As seen in Figure 4.2, basic capabilities include overall

[35] Kim, Bowon. 2015. Supply Chain Management: A Learning Perspective: Coursera Lecture. Korea Advanced Institute of Science and Technology.
[36] Kim, Bowon and Chulsoon Park. 2013. "Firms' Integrating Efforts to Mitigate the Tradeoff Between Controllability and Flexibility." International Journal of Production Research 51 (4):1258-1278.

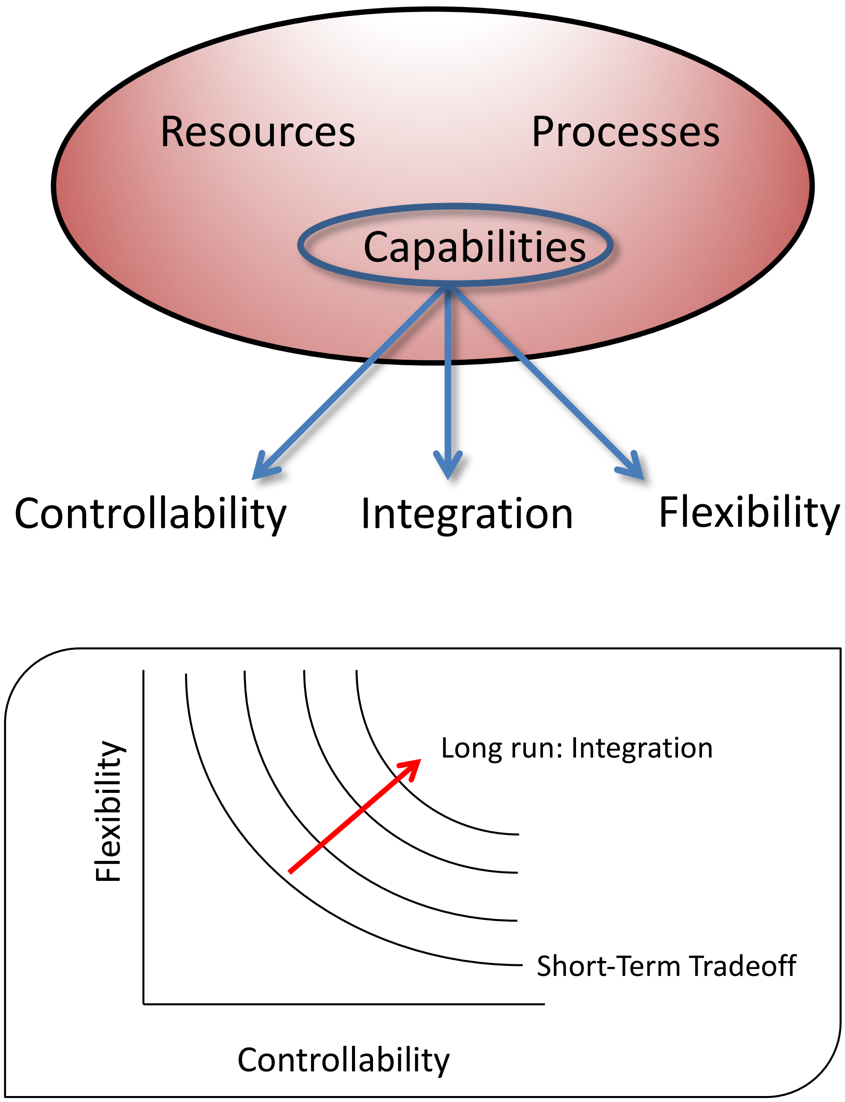

Figure 4.1: Necessities of a Firm

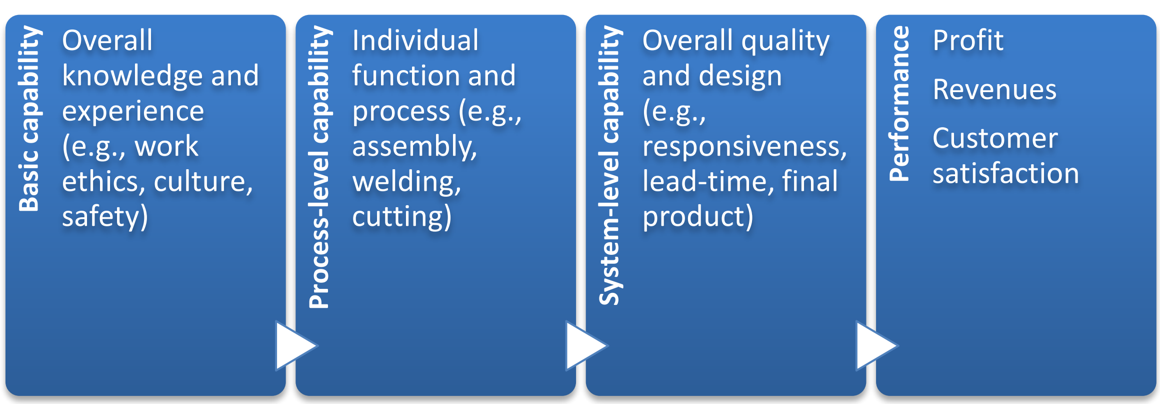

Figure 4.2: Chain of Capability

knowledge and experience of a firm and its employees, including their engineering skills, safety skills, and work ethics among other things. Process-level capabilities include individual functions such as assembly, welding, and other individual activities. System-level capabilities include bringing capabilities together to transform resources into goods and services. The final item in the chain is performance, which is often measured in profit, revenue, or customer satisfaction among other things. Adopting a new technology can impact a firm's capabilities, as it may require letting go of current knowledge and skills to adopt new ones. Processes may also change, resulting in new challenges. New technology adoption in production often affects the capabilities of a firm with the intended impact of reducing costs or increasing sales. The cost of the new technology and the certainty of the decrease in costs and/or increase in sales are significant factors in whether the new technology is adopted. The diffusion of new technologies (i.e., "the spread of an innovation throughout a social system"[37]) has a significant impact on the success of an industry and is studied in several disciplines: economics, communications, sociology, and marketing.

Rogers proposes a logistic S-curve model of diffusion, where at the early stage of diffusion there is an increasing rate, as seen in Figure 4.3.[38] Toward the end of the diffusion curve there is a decreasing rate. Early adopters of a new technology are at the left side of the curve while late adopters are at the right end. There are often great benefits for early adopters, but they are frequently accompanied with great risks.

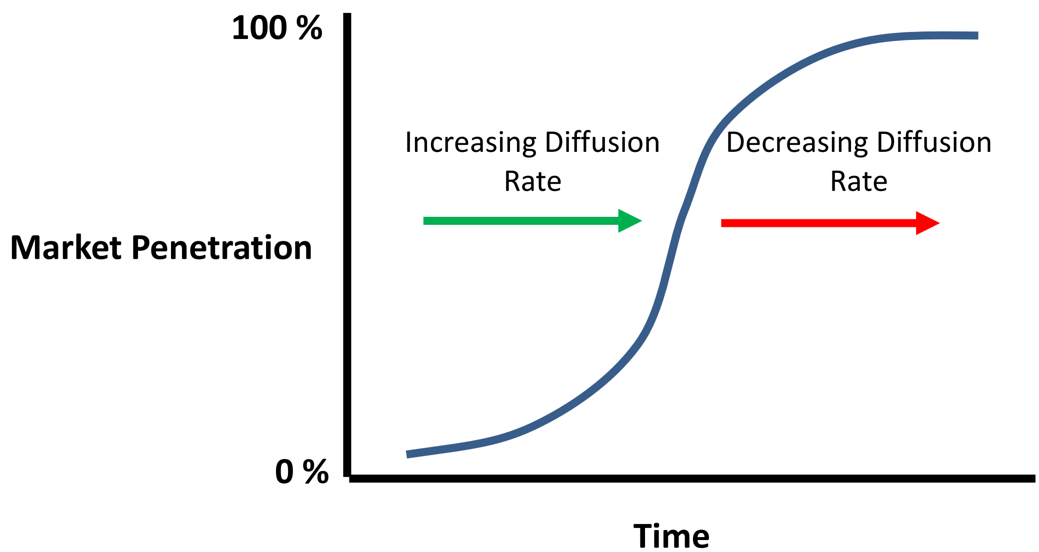

Figure 4.3: Logistic S-Curve Model of Diffusion
Modified from Rogers, E. M. 1995. *Diffusion of Innovations.* Fourth Edition (New York: The Free Press, 1995) 258.

[37] Koebel, C. Theodore, Maria Papadakis, Ed Hudson, Marilyn Cavell. 2004. The Diffusion of Innovation in the Residential Building Industry. Upper Marlboro, MD: Center for Housing Research, Virginia Polytechnic Institute and State University and NAHB Research Center.
[38] Rogers, E. M. 1995. *Diffusion of Innovations.* Fourth Edition (New York: The Free Press, 1995) 258.

A number of factors can affect how a new technology propagates through an industry or business community. The communication structure, for example, affects how people hear about a new technology. The average size of firms in an industry affects their ability to adopt new technologies, as they might not have the resources to invest in it. Rogers proposed several variables that affect the adoption and diffusion of a new technology[39]:

- Perceived attributes of innovations
- Relative advantage to the adopter
- Compatibility with other currently used products and processes
- Complexity for the adopter
- Trialability of the new technology
- Observability of the results of an innovation
- Information dissemination
- Nature of the social system (e.g. attitudes, beliefs, etc.)
- Extent of change agent promotion efforts
- Producer ability/profitability of adoption

The change in capabilities along with these other factors that affect the adoption of a new technology should be considered when contemplating adoption. For example, a firm needs to consider whether its staff can adapt to the new technology or if the new technology is compatible with their technology infrastructure. These issues may result in underestimating costs and/or overestimating benefits.

4.2. Organizational Change

A firm must not only be able to adopt a new technology, but its leaders and staff must be willing to adopt it. Skepticism and cynical attitudes among employees can disrupt seemingly sound investments. Additionally, employee resistance and distrust have resulted in the closing of factories and the decline of companies; therefore, it is critical to consider such challenges. New technologies often require employees to adopt new activities and behaviors, which results in this type of resistance. Gordon presents some of these forces[40]:

- Feelings that management ignores needs
- Ingrained schemas
- Lack of information about the new changes
- Employees fail to see a need for change
- An “us-them” attitude that pits staff against each other
- Perception of change being a threat
- Rigid organizational structures having resulted in rigid thinking

[39] Rogers, E. M. 1995. *Diffusion of Innovations.* Fourth Edition (New York: The Free Press, 1995) 258.
[40] Gordon, Judith R. Organizational Behavior: A Diagnostic Approach. Upper Saddle River, NJ: Prentice Hall, 2002). 465.

A firm that seeks to adopt new technologies will, likely, need to overcome some or all of these forces.

Overcoming old habits is difficult (i.e., costly) and it seems that many, including Deutschman, have found that facts, fear, and force alone do not cause real change to occur in people's lives or in organizations.[41] Even when people's lives are at stake (e.g., exercise and eating habits for heart patients), only about 1 out of 10 are able to change when faced with facts, fear, and force alone.[42] Deutschman suggests that three things are needed to facilitate change: relate, repeat, and reframe. "Relate" refers to creating a relationship with the relevant individuals or group. "Repeat" refers to repeating the change by practicing and reminding people of the changes implemented. Finally, "reframe" refers to presenting the change in a new light to provide other ways to think about the situation and explain why change is needed. Others suggest additional means for addressing resistance[43, 44]:

- Maintaining extensive communication with employees
- Education and training
- Employee involvement in decision making
- Facilitation and support
- Negotiation and agreement
- Implicit and explicit coercion
- New organizational structures (e.g., steering committees and task forces)
- New policies and procedures (e.g., reward systems for supporting the new changes)
- Incremental changes rather than revolutionary changes

This is not a comprehensive list of approaches; however, it provides a starting point. Many theories of change originate from Lewin, who developed a three-stage model of planned change: unfreezing, changing, and refreezing.[45] Unfreezing focuses on creating a motivation to change. The changing stage is where the organization alters some process, procedure, or other activity while freezing is the goal of maintaining the new activity.

Another well-known expert in change management, Kotter, proposed eight steps for leading change[46]:

[41] Deutschman, Alan. Change or Die: The Three Keys to Change at Work and in Life. New York, NY: Harper Business, 2007.
[42] Deutschman, Alan. Change or Die: The Three Keys to Change at Work and in Life. New York, NY: Harper Business, 2007.
[43] Gordon, Judith R. Organizational Behavior: A Diagnostic Approach. Upper Saddle River, NJ: Prentice Hall, 2002). 465.
[44] Kreitner, Robert and Angelo Kinicki. Organizational Behavior. 10th edition. New York, NY: McGraw-Hill/Irwin, 2013.
[45] Kreitner, Robert and Angelo Kinicki. Organizational Behavior. 10th edition. New York, NY: McGraw-Hill/Irwin, 2013.
[46] Kreitner, Robert and Angelo Kinicki. Organizational Behavior. 10th edition. New York, NY: McGraw-Hill/Irwin, 2013.

1. Establish a sense of urgency
2. Create the guiding coalition
3. Develop a vision and strategy
4. Communicate the change vision
5. Empower broad-based action
6. Generate short-term wins
7. Consolidate gains and produce additional change
8. Anchor the new approach in culture

These steps are based on the errors that Kotter observed in senior management and have remnants of the Lewin model. For instance, notice that the first step is similar to unfreezing while the last step is similar to unfreezing.

In addition to methodologies for implementing change, there are also methods for evaluating whether an organization is likely to be successful in adopting change. For example, Scaccia et al. present a heuristic for organizational readiness, which is described as $R = MC^2$.[47] The "R" is for readiness, while the "M" is for motivation and "C^2" is for two types of capacity. Motivation includes perceived incentives and disincentives that make an innovation attractive. These include the relative advantage, compatibility, complexity, trialability, observability, and priorities. As can be seen, five of these items overlap with Rogers' variables discussed previously. The first type of capacity in the $R = MC^2$ model is general capacity, which includes the culture, climate, organizational innovativeness, resource utilization, leadership, structure, and staff capacity. The second type of capacity is innovation specific, which includes human, technical, and fiscal conditions that are important for a particular innovation. From this framework, an instrument to assess readiness was developed and, although it is for the healthcare industry, it provides insight for activities in other industries.[48]

This section is not a comprehensive overview of methods for addressing organizational change; however, it raises the question of resistance and initiates ideas on addressing it. Firms that are considering the adoption of a new technology need to consider this issue, as it can be the difference between a successful investment and a substantial loss.

[47] Scaccia, Jonathan P., Brittany S. Cook, Andrea Lamont, Abraham Wandersman, Jennifer Castellow, Jason Katz, and Rinad S. Beidas. 2015. "A Practical Implementation Science Heuristic for Organizational Readiness: $R=MC^2$. Journal of Community Psychology 43(4). 484-501.
[48] Victoria, Scott C., Tara Kenworthy, Erin Godly-Reynolds, Gilberte Bastien, Jonathan Scaccia, Courtney McMickens, Sharon Rachel, Sayon Cooper, Glenda Wrenn, and Abraham Wandersman. The Readiness for Integrated Care Questionnaire (RICQ): An Instrument to Assess Readiness to Integrate Behavioral Health and Primary Care. American Journal of Orthopsychiatry. April 10, 2017.

5. Summary

This document serves as a concise guide to investment decision making for new technologies in manufacturing. It is not a comprehensive review of investment decision making, but rather selects those methods that can be readily applied by non-experts. In addition to presenting methods for decision making, it discusses some non-financial challenges that firms might face when adopting a new technology. For further assistance, one might consult the various finance books cited in the text or refer to a consultant.

Decision makers can select methods according to the type of decision being made (see Table 2-2). The most prominent methods used by practitioners, which include net present value and the internal rate of return, are presented in Section 2. This section also discusses some of the shortcomings of these approaches. These methods can be supplemented with the methods presented in Section 3. When considering the adoption of a new technology, decision makers should consider the potential to underestimate costs and/or overestimate benefits due to the challenges of organizational change, which is discussed in Section 4. Standard methods for categorizing costs is presented in Appendix A.

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APPENDIX A

A.1 Cost Categorization

One challenge that is frequently faced in investment analyses is the standardization of data categories. A best practice is to use standardized costs. It aids in tracking costs throughout a firm. It is also applicable in situations where costs have to be estimated using industry-wide data. Industry and occupation classification systems can be useful as a basis for categorizing costs. Two major classification systems, the North American Industry Classification System (NAICS) and the Standard Occupational Classification system (SOC), are discussed below. These systems provide a standard for tracking costs across firms and supply chains. Additionally, using these systems makes it feasible to utilize industry level data when necessary, as it is often collected in these formats. Also discussed below is a categorization of processes, which does not have a format that is as widely recognized as the NAICS or SOC systems.

A.2 Categorization of Services and Commodities

Domestic data tends to be in the North American Industry Classification System (NAICS). It is the standard used by federal statistical agencies classifying business establishments in the United States. NAICS was jointly developed by the U.S. Economic Classification Policy Committee, Statistics Canada, and Mexico's Instituto Nacional de Estadística y Geografía and was adopted in 1997.[49] NAICS has several major categories each with subcategories. Historic data and some organizations continue to use the predecessor of NAICS, which is the Standard Industrial Classification system (SIC). NAICS codes are categorized at varying levels of detail. Table A-1 presents the lowest level of detail, which is the two digit NAICS. There are 20 categories. Additional detail is added by adding additional digits; thus, three digits provides more detail than the two digit and the four digit provides more detail than the three digit. The maximum is six digits, as illustrated for automobile manufacturing (NAICS 336111) and light truck and utility manufacturing (NAICS 336112). Sometimes a two, three, four, or five-digit code is followed by zeros, which do not represent categories. They are null or place holders. For example, the code 336000 represents NAICS 336.

A.3 Labor Categorization

Federal statistical agencies classify workers into occupational categories for collecting and distributing data on employees using the Standard Occupational Classification system (SOC). The 2010 version has 840 occupations. These are categorized into 23 major groups. Occupations with similar job duties, skills, categorized into 461 broad occupations, which are categorized into 97 minor groups, education, and/or training are grouped together. Similar to the NAICS codes, additional digits represent additional detail up to a maximum of six digits, as illustrated for SOC 514011 and SOC 514012 in Table A-2, which presents the 23 major groups. The SOC classifies all occupations in

[49] US Census Bureau. North American Industry Classification System. <http://www.census.gov/eos/www/naics/>

which work is performed for pay or profit. It was first published in 1980, but was rarely utilized at that time. In 2000, it was revised and then again revised in 2010. The Bureau of Labor Statistics now publishes occupation data based on this system.

Table A-1: North American Industry Classification System, Two Digit Codes

Sector	Description
11	Agriculture, Forestry, Fishing and Hunting
21	Mining, Quarrying, and Oil and Gas Extraction
22	Utilities
23	Construction
31-33	Manufacturing
336	*Transportation Equipment Manufacturing*
3361	*Motor Vehicle Manufacturing*
33611	*Automobile and Light Duty Motor Vehicle Manufacturing*
336111	*Automobile Manufacturing*
336112	*Light Truck and Utility Manufacturing*
42	Wholesale Trade
44-45	Retail Trade
48-49	Transportation and Warehousing
51	Information
52	Finance and Insurance
53	Real Estate and Rental and Leasing
54	Professional, Scientific, and Technical Services
55	Management of Companies and Enterprises
56	Administrative and Support and Waste Management and Remediation Services
61	Educational Services
62	Health Care and Social Assistance
71	Arts, Entertainment, and Recreation
72	Accommodation and Food Services
81	Other Services (except Public Administration)
92	Public Administration

A.3 Process Categorization

Thompson (2015) provides a convenient list of manufacturing processes (see Table A-3); however, the Thompson's intention is not to provide a method of categorization.[50] Manufacturing processes do not have a standard system of classification that is as widely known as NAICS or the SOC. There are, however, a number of classification schemes, as seen in Table A-4 which is taken from Mani et al. (2013). Each of the schemes shown have advantages and a different basis for classification.

[50] Thompson, Rob. Manufacturing Processes for Design Professionals. New York, NY: Thames & Hudson, 2015.

Table A-2: Standard Occupational Classification System, Two Digit Codes

Occupation Code	Occupation Name
11	Management Occupations
13	Business and Financial Operations Occupations
15	Computer and Mathematical Occupations
17	Architecture and Engineering Occupations
19	Life, Physical, and Social Science Occupations
21	Community and Social Service Occupations
23	Legal Occupations
25	Education, Training, and Library Occupations
27	Arts, Design, Entertainment, Sports, and Media Occupations
29	Healthcare Practitioners and Technical Occupations
31	Healthcare Support Occupations
33	Protective Service Occupations
35	Food Preparation and Serving Related Occupations
37	Building and Grounds Cleaning and Maintenance Occupations
39	Personal Care and Service Occupations
41	Sales and Related Occupations
43	Office and Administrative Support Occupations
45	Farming, Fishing, and Forestry Occupations
47	Construction and Extraction Occupations
49	Installation, Maintenance, and Repair Occupations
51	Production Occupations
514	*Metal Workers and Plastic Workers*
5140	*Metal Workers and Plastic Workers*
51401	*Computer Control Programmers and Operators*
514011	*Computer-Controlled Machine Tool Operators, Metal and Plastic*
514012	*Computer Numerically Controlled Machine Tool Programmers, Metal and Plastic*
53	Transportation and Material Moving Occupations
55	Military Specific Occupations

The National Research Council (NRC), for example, has a committee on unit manufacturing process research that identifies unit processes as a basis for classification.[51] According to NRC, there are five physical process categories:

1. **Mass-change processes**, which remove or add material by mechanical, electrical, or chemical means (included are the traditional processes of machining, grinding, and plating, as well as such nontraditional processes as electrodischarge and electrochemical machining)
2. **Phase-change processes**, which produce a solid part from material originally in the liquid or vapor phase (typical examples are the casting of metals, the manufacture of composites by infiltration, and injection molding of polymers)

[51] Unit Manufacturing Process Research Committee, National Research Council. Unit Manufacturing Processes: Issues and Opportunities in Research. Washington DC: The National Academic Press, 1995.

3. **Structure-change processes**, which alter the microstructure of a workpiece, either throughout its bulk or in a localized area such as its surface (heat treatment and surface hardening are typical processes within this family; the family also encompasses phase changes in the solid state, such as precipitation hardening)
4. **Deformation processes**, which alter the shape of a solid workpiece without changing its mass or composition (classical bulk-forming metalworking processes of rolling and forging are in this category, as are sheet-forming processes such as deep drawing and ironing)
5. **Consolidation processes**, which combine materials such as particles, filaments, or solid sections to form a solid part or component (powder metallurgy, ceramic molding, and polymer-matrix composite pressing are examples, as are joining processes, such as welding and brazing).

A more recognized taxonomy of processes is presented by Todd et al. (1994).[52] Table A-5 presents a manufacturing process classification based on their taxonomy. For this report, a process code was developed similar to that of the NAICS and SOC and applied to their taxonomy. It is a six digit code where additional detail is added by adding additional digits; thus, three digits provides more detail than the two digit and the four digit provides more detail than the three digit. Unfortunately, the taxonomy presented by Todd et al is over 20 years old; therefore, there is, likely, a need to incorporate more recent developments for this taxonomy to be completely relevant.

[52] Todd, Robert H., Dell K. Allen, and Leo Alting. Manufacturing Processes Reference Guide. New York, NY: Industrial Press, Inc, 1994. xiii-xxiv.

Table A-3: Manufacturing Process Categories

Category	Process
Plastics and Rubber	Blow molding
	Thermoforming
	Rotation molding
	Vacuum casting
	Compression molding
	Injection molding
	Reaction injection molding
	Dip molding
Metal	Panel beating
	Metal spinning
	Metal stamping
	Deep drawing
	Superforming
	Tube and section bending
	swaging
	Roll forming
	Forging
	Sand casting
	Die casting
	Investment casting
	Metal injection molding
	Electroforming
	Centrifugal casting
	Press braking
Glass and Ceramics	Glassblowing
	Lampworking
	Clay throwing
	Ceramic slip casting
	Press molding ceramics
Wood	CNC machining (wood and other)
	Wood laminating
	Steam bending
	Paper pulp molding
Composites	Composite laminating
	DMC and SMC molding
	Filament winding
	3D Thermal laminating

Category	Process
Layered	Additive manufacturing
Cutting	Photochemical machining
	Laser cutting
	Electrical discharge machining
	Punching and blanking
	Die cutting
	Water jet cutting
	Glass scoring
Joining	Arc welding
	Power beam welding
	Friction welding
	Vibration welding
	Ultrasonic welding
	Resistance welding
	Soldering and brazing
	Staking
	Hot plate welding
	Joinery
	Weaving
	Upholstery
	Timber frame structures
Finishing Technology	Spray painting
	Powder coating
	Anodizing
	Electroplating
	Galvanizing
	Vacuum metalizing
	Grinding, sanding, and polishing
	Electropolishing
	Abrasive blasting
	Photo etching
	CNC Engraving
	Screen printing
	Pad printing
	Hydro transfer printing
	Foil blocking and embossing

Source: Thompson, Rob. Manufacturing Processes for Design Professionals. New York, NY: Thames & Hudson, 2015.

Table A-4: Selection of Manufacturing Process Classifications

	Source					
	NRC	Todd et al	DIN 8580	Paul DeGarmo	Ashby	Mil
Classification	Five families of physical processes • Mass-change processes • Phase-change processes • Structure-change processes • Deformation processes • Consolidation processes	Six families of Shaping processes • Mass Reducing • Thermal Mass Reducing • Chemical Mass Reducing • Mass Conserving • Consolidation • Joining Four families of Non-shaping processes • Hardening • Softening • Surface Preparation • Surface Coatings	Six groups of manufacturing processes • Original Forming • Transforming • Separating • Joining • Coating and Finishing • Change of Material Properties	Seven types are identified • Casting or Molding • Forming or Shearing • Machining (material removal) • Heat Treating • Finishing • Assembly • Inspection	Four groups of manufacturing processes • Primary shaping processes: • Secondary processes: • Joining • Finishing	Manufacturing Management Taxonomy • Product Design • Process Design& Control • Supply Chain Management
Basis of classification	Physical change	Shaping/Non-shaping	Forming/ Transforming/ Material Property	Casting/Forming/ Material Property	Primary/ Secondary	Manufacturing Management
Advantages	Science-based	Ease of use	Being used in CO2PE! effort for determining LCI of Manufacturing Processes	Simple	Simple	Management

Source: Mani, Mahesh, Jatinder Madan, Jae Hyun Lee, Kevin W. Lyons, and Satyandra K. Gupta. 2013. Review on Sustainability Characterization for Manufacturing Processes. NISTIR 7913. http://nvlpubs.nist.gov/nistpubs/ir/2013/NIST.IR.7913.pdf

Table A-5: Manufacturing Process Classification (Based on Todd et al. 1994)

Process Code	Description	Process Code	Description
100000	Shaping	112330	Ion Beam Cutting
110000	Mass Reducing	113000	Chemical Reducing
111000	Mechanical Reducing	113100	Chemical Milling
111100	Reducing (chips)	113110	Immersion Chemical Milling
111110	Single-Point Cutting	113120	Spray Chemical Milling
111111	Turning/Facing	113200	Electrochemical Milling
111112	Boring	113210	Cavity-Type
111113	Shaping/Planing	113220	Grinder-Type
111114	Parting/Grooving	113300	Photochemical Milling
111115	Threading (SP)	113310	Photo Etching
111120	Multipoint Cutting	113320	Photo Milling
111121	Drilling	120000	Mass Conserving
111122	Reaming	121000	Consolidation
111123	Milling/Routing	121100	Casting - Nonreusable
111124	Broaching	121110	Ceramic Mold Casting
111125	Threading (MP)	121111	Investment Casting
111126	Filing	121112	Plaster Mold Casting
111127	Sawing	121120	Sand Mold Casting
111128	Gear Cutting	121121	Sand Casting
111130	Abrasive machining	121122	Shell Mold Casting
111131	Grinding	121123	No-Bake Mold Casting
111132	Honing	121124	Full-Mold Casting
111133	Lapping	121200	Casting - Reusable Mold
111134	Superfinishing	121210	Die Casting
111135	Ultrasonic Machining	121220	Permanent Mold Casting
111136	Jet Machining	121230	Flexible Mold Casting
111200	Seperating (shear)	121240	Continuous Casting
111210	Shearing	121300	Molding
111211	Squaring	121310	Ceramic Molding
111212	Slitting	121311	Wet Forming
111213	Rotary Shearing	121312	Dry Pressing
111214	Nibbling	121320	Polymer Molding
111220	Blanking	121321	Injection Molding
111221	Conventional Blanking	121322	Blow Molding
111222	Steel-Rule-Die Blanking	121323	Transfer Molding
111223	Fine Blanking	121324	Compression Molding
111224	Shaving/Trimming	121325	Extrusion Molding
111225	Dinking	121326	Thermoform Molding
111230	Piercing	121327	Rotational Molding
111231	Punching	121400	Compacting
111232	Perforating	121410	Continuous Compacting
111233	Lancing	121411	Powder Material Extrusion
111234	Notching	121412	Powder Material Rolling
112000	Thermal Reducing	121420	Noncontinuous Compacting
112100	Torch Cutting	121500	Deposition
112110	Air Arc Cutting	121510	Electroforming
112120	Gas Cutting	121600	Laminating
112130	Plasma Arc Cutting	121610	Filament Winding
112200	Electrical Discharge Machining (EDM)	121620	Sheet Laminating
112210	Cavity-Type	121630	Bulk Laminating
112220	Grinding	121631	Spray Lay-up
112230	Sawing	121632	Hand Lay-up
112300	High Energy Beam Machining	121640	Pultrusion
112310	Electron Beam Cutting	122000	Total Deformation
112320	Laser Beam Cutting	122100	Forging

Process Code	Description	Process Code	Description
122110	Hot Forging	131200	Inertial Friction Welding
122111	Hammer Forging	131300	Ultrasonci Welding
122112	Drop Forging	131400	Explosive Welding
122113	Press Forging	132000	Thermal Joining
122114	Upset Forging	132100	Thermal Welding
122115	Roll Forging	132110	Electric Arc Welding
122120	Cold Forging	132111	Shielded Metal Arc Welding
122200	Extruding	132112	Gas Metal Arc (MIG) Welding
122210	Direct Extrusion	132113	Gas Tungsten Arc (TIG) Welding
122220	Indirect Extrusion	132114	Submerged Arc Welding
122230	Impact Extrusion	132115	Carbon Arc Welding
122300	Drawing	132116	Stud Welding
122310	Wire Drawing	132120	Electrical Resistance Welding
122320	Tube Drawing	132121	Spot Welding
122400	Rolling	132122	Seam Welding
122410	Sheet Rolling	132123	Projection Welding
122420	Foil Rolling	132124	Butt Welding
122430	Structural Rolling	132125	Percussion Welding
122440	Pierce Rolling	132126	Electroslag Welding
122500	Shear Spinning	132130	Gas/Chemical Welding
122600	Coining/Sizing/Hobbing	132131	Combustible Gas Welding
122700	Thread Forming	132132	Atomic Hydrogen Welding
122800	Knurling	132140	Braze Welding
123000	Local Deformation	132141	Gas Brazing
123100	Bending	132142	Carbon Arc Brazing
123110	Straight Angle Bending	132150	Diffusion Bonding
123120	Corrugation Bending	132160	High Energy Beam Welding
123130	Joggle Bending	132161	Electron Beam Welding
123140	Curling	132162	Laser Beam Welding
123150	Seaming	132163	Plasma Arc Welding
123160	Tube Bending	132200	Brazing
123170	Roll Forming	132210	Infrared Brazing
123200	Conventional Sheeting Forming	132220	Resistance Brazing
123210	Die Forming: Matched Die Drawing	132230	Torch Brazing
123211	Simple Rigid Die	132240	Dip Brazing
123212	Compound Die	132250	Furnace Brazing
123213	Progressive Die	132260	Induction Brazing
123220	Die Forming: Rubber Die Drawing	132300	Soldering
123221	Guerin Process	132310	Friction/Ultrasonic Soldering
123222	Martform Process	132320	Induction Soldering
123223	Hydroform Process	132330	Infrared Soldering
123230	Conventional Spinning	132340	Dip Soldering
123240	Stretch Forming	132350	Iron Soldering
123250	Embossing	132360	Resistance Soldering
123300	Conventional Tube Forming	132370	Torch Soldering
123310	Swaging	132380	Wave Soldering
123320	Flaring	133000	Chemical Joining: adhesive bonding
123330	Intraforming	200000	Nonshaping
123400	High Energy Rate Forming	210000	Heat Treatment
123410	Explosive Forming	212000	Annealing
123420	Electromagnetic Forming	212100	Recovery
123430	Electrohydraulic Forming	212110	Stress Relieving
130000	Joining	212120	Tempering
131000	Mechanical Joining	212200	Recrystallization
131100	Cold Pressure Welding	212210	Full Annealing

Process Code	Description	Process Code	Description
212220	Process Annealing	222000	Surface Coating
212230	Short-Cycle Annealing	222100	Mechanical Coating
213000	Hardening	222110	Spray Coating: Pressure Transferred
213100	Surface Hardening	222111	Air Gun Spraying
213110	Carburizing	222112	High Pressure Airless Spray
213120	Chromizing	222120	Spray Coating: Charged Transferred
213130	Carbonitriding	222121	Electrostatic Coating
213140	Cyaniding	222122	Vacuum Coating
213150	Nitriding	222130	Dip/Flow Coating
213160	Diffusion Hardening	222131	Cold Dip Coating
213170	Flame Hardening	222132	Hot Dip Coating
213180	Induction Hardening	222133	Electrocoating
213200	Through Hardening	222134	Fluidized Bed Coating
213210	Water Quench Hardening	222135	Curtain Coating
213220	Oil Quench Hardening	222140	Dust Coating
213230	Air Quench Hardening	222150	Roll Coating
213240	Martempering	222151	Calendering
213250	Austempering	222152	Roller Coating
213260	Age Hardening	222200	Thermal Coating
214000	Other Heat Treatment	222210	Flame Spraying
214100	Sintering	222211	Combustion Flame Spraying
214110	Solid-Phase Sintering	222212	Plasma Arc Spraying
214120	Liquid-Phase Sintering	222213	Detonation Gun Spraying
214200	Subzero Cold Treatment	222220	Vaporized Metal Coating
214300	Firing/Glazing	222221	Vacuum Metallizing
214400	Curing/Bonding	222222	Sputtering
220000	Surface Finish	222223	Chemical Vapor-Phase Deposition
221000	Surface Preparation	222230	Heat Tinting
221100	Descaling	222300	Chemical Coating
221110	Mechanical Descaling	222310	Electroplating
221111	Abrasive Blasting	222320	Chemical Conversion
221112	Belt Sanding	222321	Anodize
221113	Shot Peening Preparation	222322	Alkaline Oxide
221114	Wire Brushing	222323	Fused Nitrate
221115	Grinding	222324	Proprietary Treatments
221120	Thermal Descaling	222325	Phosphate
221121	Flame Cleaning	222326	Chromate
221130	Chemical Descaling	223000	Surface Modification
221131	Chemical Pickling	223100	Burnishing
221200	Deburring	223200	Peening
221210	Mechanical Deburring	223210	Shot Peening
221211	Barrel Tumbling	223220	Hammer Peening
221212	Vibratory Finishing	223300	Texturing
221213	Knife Deburring	223310	Wire Brush Finishing
221220	Thermal Deburring	223320	Buffing/Polishing
221221	Thermochemical Deburring		
221230	Chemical Deburring		
221231	Electrochemical Deburring		
221300	Degreasing		
221310	Mechanical Degreasing		
221311	Ultrasonic Degreasing		
221320	Chemical Degreasing		
221321	Vapor Degreasing		
221322	Solvent Degreasing		
221323	Alkali Degreasing		

Source: Todd, Robert H., Dell K. Allen, and Leo Alting. Manufacturing Processes Reference Guide. New York, NY: Industrial Press, Inc, 1994. xiii-xxiv.