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ABSTRACT

"Critical fixities," the inflexibility of a firm to change, are defined and explained in this study. Implications of leap-frog type competitions, entry strategy, vertical integration, and timing of investment are derived. The U.S. steel industry is used as an example to illustrate these implications.

Introduction

One of the most significant industrial transformations in the last twenty years in the U.S. is the decline of the smokestack industries such as the automobile and steel industries. The major reason for this decline is the inability of these industries to compete with their international rivals. High labor costs and obsolete equipment have been cited as the main causes in this loss of international competitiveness. Although high labor costs should have induced firms to replace less efficient equipment with new labor-saving technologies which have been universally available in these industries, it seems strange that steelmakers and automakers suffering from high labor costs have not aggressively adopted these labor-saving technologies. One possible explanation for this seemingly contradictory phenomenon, as argued below, is the notion of critical fixities, an inertia that keeps a firm from responding to change. More specifically, this paper illustrates that, despite high labor costs, critical fixities could have contributed to the slow adoption of new technologies and thus caused the decline of the steel industry.

This paper is divided into three sections. The first section examines and explains theoretical foundations of critical fixities. The second section deals with strategic implications of critical fixities. The third section discusses the steel industry as an example of the application of critical fixities.

THE NOTION OF CRITICAL FIXITIES

It is generally recognized that a firm's strategy should be adapted to environmental change. The ability of a firm to adapt to environmental changes is crucial to the firm's long-term success. For technology intensive industries, a firm's willingness and ability to adapt to technological changes in order to maintain its competitiveness is especially critical to its survival. In a process technology intensive industry such as the steel industry, the vintage of process technologies affects a firm's competitiveness to a great extent. Consequently, a key strategic issue is how to adopt process innovations in order to avoid the threats from as well as to exploit these innovations. A firm adopts a process innovation either during the expansion process or for replacement reasons. Since opportunities for expansion are few in mature industries such as the steel industry, we will explore the ability to adopt process innovations based on the replacement theory.

Two main conclusions can be drawn from the replacement theory. First, assuming that a firm does not retrench from production and that existing equipment eventually wears out, the decision regarding replacement is not whether to replace the equipment but, rather, when to do it. Second, since previous investment in the existing equipment is a sunk cost, a firm should replace its equipment when the marginal cost of the existing equipment equals the average cost of the new equipment, assuming an absence of technological change [Fama and Miller, 1972; Nickell, 1978; Salter, 1960; Terborgh, 1949]. However, this proposition does not hold under continuous technological change. The main reason is that as new equipment is installed and technology progresses, the new equipment begins to accumulate "operating inferiority" relative to newer technologies which will emerge in the future. As Terborgh [1949] argued:

> It is true that the challenger has eliminated all present available rivals. But it has not eliminated future rivals. The latter, though at present mere potentialities, are important in the contest. For the current challenger can make good its claim to succeed the defender only when there are no future challengers worth waiting for. It must engage, as it were, in a two-front war, attacking on one side the aged machine it hopes to dislodge and on the other side an array of rivals still unborn who also hope to dislodge the same aged machine, but later. (p. 55)

This assertion clearly illustrates the dilemma a firm faces in replacing its technologically inferior equipment. If the firm waits for more advanced equipment by delaying its replacement, it will have to bear higher marginal costs over the delay period. But if the firm replaces its obsolete equipment now, it gives up the opportunity to adopt more advanced equipment in the future, which would yield more cost savings. This dilemma is shown graphically in Figure 1. $MC(t)_{old}$ denotes the marginal cost of the existing equipment at time t and $AC(t)_{new}$ denotes the average cost of the new equipment installed at time t. To simplify the problem, we assume that (i) there are no switching costs involved, (ii) the average cost of new equipment declines over a finite period of time as a result of technological advances, and (iii) marginal cost of the existing equipment increases over time because of age.

Insert Figure 1 about here

Without considering technological progress, the firm will replace its existing equipment at T' when its marginal cost equals the average cost of the new, BT'. We assume that the new equipment will last till T''' and then be replaced with a residual value RV_1. The total cash outflow till time T''' is OABFT''' minus RV_1. OABFT''' is the sum of the cash outflow of using the old equipment, OABT', and the cash outflow of using the new, BT'T'''F. But under continuing technological obsolescence, the firm may benefit from delaying replacement of its equipment.

If the firm delays its replacement till T'', its average cost of using the new equipment will be T''E. Let this piece of equipment last till time T and have a residual value RV_2. In this case, its cash outflow till T is OACT'' plus ET''TJ minus RV_2. The difference in cashflows between the two alternatives is (BCD - DEGF + GHIJ + $RV_1 - RV_2$), discounted by the cost of capital. If discounted BCD + GHIJ is less than discounted DEGF + $RV_2 - RV_1$, the firm is better off by waiting till T'' and then replacing its equipment. In this case, the high marginal costs incurred during the period from T' to T'' are well compensated by the low average cost of new equipment available in T''.

Given the benefits and costs of waiting, the problem facing the firm is how to choose the optimal time to replace its equipment. The mathematical model derived below will obtain the optimal timing of replacement under continuous technological change. Although the model is not intended to be realistic, we believe that the results derived are of general importance. We first make the following assumptions to construct the model:

1. The firm maximizes the present value of its investment.
2. The market is relatively competitive and thus the firm is a price taker.
3. Uncertainty is absent.

4. There are no taxes of any description.
5. The marginal cost of equipment increases with the age of the equipment.
6. The cost of captial is constant over time.
7. New equipment reduces production costs but does not add to the quality of the product and does not change the value of the firm's output.
8. The firm replaces its equipment only once in the planning horizon.[1]
9. Technology progresses over time and thus the production cost declines over time.
10. The replacement takes place instantaneously.

Since the firm is a price taker and new equipment does not change the value of its output, the replacement decision will not affect the firm's revenues. Thus, the objective of the replacement is cash outflow minimization. If the replacement takes place at an arbitrary time T', the cash outflow from time zero to T is

Cashflow = [Marginal cost of the existing equipment till T'] + (Investment in the new equipment + Marginal cost of operating the new equipment - Residual value of the equipment at time T)

in which the net investment in the new equipment is the sum of the fixed cost of the equipment plus switching costs, minus the salvage value of the old equipment. We let

- r be the cost of capital which remains constant.
- T be the planning horizon of the replacement decision.
- T' be the timing of replacement.
- I(t) be the fixed cost of the new equipment plus switching costs minus salvage value of the old equipment at time t.

- MC(T',s) be the marginal cost of new equipment of age s, which is is installed at time T'.
- RV(T') be the residual value at T of the equipment installed at T'.

The cash outflow of operating the existing equipment till time T' and then replacing the equipment is

$$C = \int_0^{T'} MC(t)e^{-rt}\,dt + e^{-rT'}\left(I(T') + \int_0^{T-T'} MC'(T',s)e^{-rs}ds\right)$$

$$- RV(T')e^{-rT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

To minimize the cash flow, differentiating equation 1 with respect to T' we get

$$\frac{dC}{dT'} = MC(T')e^{-rT'} - re^{-rT'}\left[(I(T') + \int_0^{T-T'} MC'(T',s)e^{-rs}\,ds)\right]$$

$$+ e^{-rT'} * \frac{dI(T')}{dT'} + e^{-rT'} * \frac{d}{dT'} \int_0^{T-T'} MC'(T',s)e^{-rs}\,ds$$

$$- \frac{dRV(T')}{dT'}\, e^{-rT}$$

Canceling $e^{-rT'}$ gives

$$MC(T') - rI(T') + \frac{dI(T')}{dT'} - \frac{dRV(T')}{dT'}\, e^{-r(T-T')} + \int_0^{T-T'} -rMC'(T',s)e^{-rs}ds$$

$$+ \frac{d}{dT'} \int_0^{T-T'} MC'(T',s)e^{-rs}ds \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The last two terms need further simplification. Using integral by parts we get

$$\int_0^{T-T'} -rMC'(T',s)e^{-rs}\,ds = \int_0^{T-T'} -re^{-rs}\,ds\;MC'(T',s)$$

$$= e^{-rs}MC'(T',s)\Big|_0^{T-T'} - \int_0^{T-T'} \frac{d}{ds}\,MC'(T',s)e^{-rs}ds$$

$$= e^{-r(T-T')}MC'(T',T-T') - MC'(T',0)$$

$$- \int_0^{T-T'} \frac{d}{ds}\,MC'(T',s)e^{-rs}ds\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The last term in equation (2) is

$$\frac{d}{dT'}\int_0^{T-T'} MC'(T',s)e^{-rs}ds$$

$$= \int_0^{T-T'}\frac{d}{dT'}\,MC'(T',s)e^{-rs}ds - MC'(T',T-T')e^{-r(T-T')}\ldots\ldots(4)$$

Substituting (3) and (4) into (2) gives

$$MC'(T')-rI(T')\,\frac{dI(T')}{dT'} - \frac{dRV(T')}{dT'}\,e^{-r(T-T')} + e^{-r(T-T')}MC'(T',T-T')$$

$$-MC'(T',0) - \int_0^{T-T'}\frac{d}{ds}MC'(T',s)e^{-rs}ds + \int_0^{T-T'}\frac{d}{dT'}MC'(T',s)e^{-rs}ds$$

$$-MC'(T',T-T')e^{-r(T-T')}$$

which is equal to

$$MC(T') + [\frac{dI(T')}{dT'} + \int_0^{T-T'} \frac{d}{dT'} MC'(T',s)e^{-rs}\,ds - \frac{dRV(T')}{dT'}e^{-r(T-T')}]$$

$$-rI(T') - MC'(T',0) - \int_0^{T-T'} \frac{d}{ds} MC'(T',s)e^{-rs}ds \ldots\ldots\ldots\ldots (5)$$

Setting equation 5 to zero represents the first order condition of cash outflow minimization. Solving for T' we get the optimal timing of replacement for the existing equipment. Before proceeding to the implications of this equation, an understanding of the economic interpretations of the terms in equation 5 must be achieved. Consider $dI(T')/dT'$,

$$\int_0^{T-T'} \frac{d}{dT'} MC'(T',s)\, e^{-rs}ds \text{ and } \frac{dRV(T')}{dT'}\, e^{-r(T-T')}.$$

The first expression reflects the effects of the timing of equipment replacement on the investment cost, I, which includes the salvage value of the old equipment, the purchase price of the new equipment, and the switching costs. The second and third expressions reflect the timing effect on the marginal cost and the residual value of the new equipment. Since technology progresses over time, the sum of these three expressions can be viewed as the net effect of technological progress on those costs. If switching costs are constant over time and the salvage value is minimum, then the sum of these three expressions should be negative because (i) the residual value of the equipment at T increases with T' and thus $(\frac{dRV(T')}{dT'} e^{-r(T-T')})$ is negative and (ii) as technology progresses, the average cost of new equipment, including fixed costs and marginal costs, is reduced. These costs reductions, represented by the absolute value of the sum of these two expressions, are the economic gains in costs obtained by waiting for a more advanced technology.

Next we consider the expression $[MC'(T',0) + \int_0^{T-T'} \frac{d}{ds}MC'(T',s) e^{-rs}ds]$. MC'(T',0) is the marginal cost of the equipment installed at T' when it is new. The expression $\int_0^{T-T'} \frac{d}{ds}MC'(T',s)e^{-rs}ds$ represents the averaged, time adjusted increases in the marginal cost of the new equipment. Thus, the sum of these two terms is the time-adjusted marginal cost of the new equipment averaged over the period from T' to T. To this sum we add rI(T'), the net investment times cost of capital which gives us the average cost of the new equipment. The economic interpretations of these terms are now apparent and we can therefore begin the discussion of the implications of equation 5.

In setting equation 5 to zero and rearranging it, we obtain

$$MC(T') + [\frac{dI(T')}{dT'} + \int_0^{T-T'} \frac{d}{dT'} MC'(T',s)e^{-rs} ds - \frac{dRV(T')}{dT'} e^{-r(T-T')}]$$

$$= rI(T') + MC'(T',0) + \int_0^{T-T'} \frac{d}{ds}MC'(T's)e^{-rs} \text{.........}(6)$$

This is the necessary condition for the firm to minimize its discounted cash outflows. Further break down of investment into fixed costs of the new equipment and switching costs gives

$$MC_{old} - \text{Gains in costs from waiting} = AC_{new} + \text{Switching costs} \quad (7)$$

Equation 7 indicates that the firm should replace its existing equipment when the marginal cost of the old equipment minus economic gains from delaying replacement of the equipment equals the average cost of the new equipment plus switching costs. This proposition has eight important strategic implications.

STRATEGIC IMPLICATIONS OF CRITICAL FIXITIES

First, equation 7 demonstrates that, other things being equal, the lower the marginal cost and the higher the switching costs, the less likelihood there is that the firm will replace its existing equipment with new equipment. These effects can be viewed as the fixities of a firm to adopt a process innovation. As suggested by Zannetos, et.al. [1982], high switching costs and low marginal cost result from critical fixities of the firm. As we stated earlier, the term "critical fixities" means an inertia that keeps an organization from responding, from adopting, and from innovating, strategies which are critical to the decision of the firm and, ultimately, to its survival. This inertia is related to three major factor inputs: capital, labor, and management. Thus, critical fixities consist of capital fixity, labor fixity, and managerial fixity; and each represents the inflexibility of a factor input in adapting to an innovation.

Capital fixities reflect the amount of inertia associated with physical capital which is manifested in the marginal cost and switching costs. Low marginal costs result from efficient operations and a high degree of vertical integration. As capital successfully substitutes for labor and vertical integration substitutes for materials purchased, sunk cost increases and marginal costs decrease. As a result, it becomes less attractive to adopt advanced equipment. Likewise, as capital stock increases through investment in either cost saving equipment or in vertical integration, switching costs associated with capital are likely to increase. Both low marginal costs and high switching costs restrain change. In other words, the investment in capital goods reflects the commitment of the firm to a certain technology. By making the commitment, the firm becomes locked into that technology and the investment becomes a barrier to exit from that technology. Following this, previous investments may become an exit barrier from an industry, a notion discussed by Caves and Porter [1976], and Harrigan [1980].

Labor fixities refer to inertia on the part of blue collar workers (production workers) that impinges on management's ability to adequately respond to change. This restraining may be due to organizational or power issues, often related to unions, or simply to the inability of workers to change or to adapt to an innovation.

Labor union power plays an interesting role in labor fixities because it simultaneously increases the marginal cost of the existing labor force through higher wages while increasing the average switching costs of restraining through political opposition. On the one hand, unions help the adoption of innovation, while hindering it on the other. It is difficult to say which effect is likely to predominate. In some cases, unions transfer high labor costs into fixed costs through setting strict work rules, reducing marginal cost and prohibiting innovation adoptions.[2]

Also, the operational activities of a firm help to increase labor fixities. Firms seek to reduce costs through specialization of labor. This specialization, coupled with volume production, allows workers to move down the experience curve with the effect of reducing unit costs over time. Thus, the total marginal costs will decline, making the existing technology more and more attractive. However, there is a danger that the more this occurs, the greater the switching cost involved in retraining workers for a new technology will be.

Managerial fixities reflect the inability or unwillingness of management to innovate or adopt innovations when it is economically feasible to do so. No doubt, this factor is multi-dimensional. It may partially be due to psychological resistance to change which may result from high personal switching costs to the new technology and a specialization in the old technology. Thus, the longer a manager stays in the same job, the higher the specialization and the more difficult it is to change. Another dimension of managerial fixity may be organizational structure, i.e., the way the organization is structured may limit the degree of change or even the ability to recognize it.

In sum, capital fixities cause low marginal costs and high switching costs; labor and managerial fixities increase switching costs. These low marginal costs and high switching costs prohibit adoption of a process innovation for replacement.

Equation 7 demonstrates the economic consequences of the three fixities; it can also help us examine how critical they are in decisions made by the firm.

Considering equation 7 more carefully, it can be seen that it also implies that a firm should stand accounting losses rather than replace its out-of-date equipment. If other firms gradually adopt the process innovation, the price is likely to be the average cost of the new equipment including the minimum return on capital. Substituting price for AC_{new} into equation 7 gives

$$MC_{old} - \text{Price} = \text{Gains from waiting} + \text{Switching costs} > 0 \quad (8)$$

Since switching costs and, thus, the right hand side of the equation are most likely to be positive, the implication is that even if the marginal cost exceeds the price, the firm still does not replace its equipment. Since the marginal cost is the cash outflow and the price is the cash inflow, when the marginal cost exceeds the price, there is an accounting loss or even a negative cashflow. Facing continuous technological change, a firm should suffer an accounting loss or even a negative cashflow and still keep its out-moded equipment. If the firm's cash reserve cannot be sustained long enough to wait for the adverse effects of critical fixities to subside, the firm will go bankrupt. Therefore, these fixities are critical to a firm's survival. In fact, as we will show later, critical fixities have caused the decline of at least one entire industry.

The fact that a firm should suffer accounting losses and still keep its out-moded equipment provides an economic rationale for the "deindustrialization" of America.[3] Probably due to critical fixities, U.S. firms are not willing to nor should they switch to modern equipment, despite their losses. Therefore, some industries become de-industrialized. It is hard to argue that firms in these industries are short-sighted. As suggested before, the decision of replacement is not whether to replace but when to replace. These firms may have a long-term perspective and are waiting for more advanced technologies. Simply rushing to the most up-to-date equipment, according to our model, may precisely reflect a short-term view in that it provides the firm with only a short-term cost advantage.

Third, the critical fixities model also provides an explanation of the entry and exit resulting from technological innovations. While existing firms are reluctant to adopt new technologies because of critical fixities, other firms may enter the market and adopt the new technology, resulting in a lower cost, and thus, an extra profit. Entrants with new technologies may force existing firms with high critical fixities to exit from the industry.

This seems to suggest an entry with new technology strategy. That is, as critical fixities of incumbent firms prevent them from adopting the new technology, entrants can easily out-perform the existing firm by adopting the new technology which leads to a lower cost or a higher value. This strategy seems to be adopted widely. For example, Amdal came to the IBM-compatible mainframe computer industry with ECL (Emitter-Coupled-Logic): ten years later IBM adopted the ECL for its Sierra Series. Japanese industries are the most notable examples of successfully employing this strategy. The Japanese entered the U.S. auto industry with robotic technology, the semiconductor industry with CMOS[4] (Complementary Metal-Oxide Semiconductor), and the steel industry with gigantic blast furnaces and the Basic Oxygen Furnace. However, this strategy should be used cautiously because critical fixities also imply leap-frog type competition.

Leap-frog type competition is thus the fourth implication of this model. We let the history of an industry be divided into N periods and assume that a process innovation occurs at the beginning of each period. We also assume that N periods are so divided that the process innovation introduced in period N+1 is not, due to critical fixities, economically attractive and the technology of period N is not replaced. But, as the marginal cost of production increases over time, the technology introduced in period N+1 is economically attractive enough to replace the technology of period N-1. Therefore, at period N+1, while the firms which adopted the technology of period N are not willing to adopt the advanced technology of period N+1, entries and exits may occur and firms which adopted the technology of period N may suffer accounting losses over period N+1. However, in period N+2, those firms with period N technology will be willing to adopt the technology available during period N+2, while the firms with period N+1 technology will not be willing to do so because of their critical fixities. Consequently, in period N+2, the firms which suffer losses in period N+1 become winners and the winners in period N+1 become losers. Leap-frog type competition is thus manifested: some firms enjoy a short period of gain and, subsequently, a short period of loss. As we shall show later, this may explain the rise of U.S. steel industry in the '50s and then its fall in the subsequent decades.

The leap-frog type competition described above indicates that competitive cost advantages will not be substainable if the advantages are achieved through investing in modern machine and equipment. Although investing in modern process technologies leads to a lower cost now, the investing firms will incur critical fixities and then be surpassed by firms using future technologies. It seems that, according to this model, modernizing equipment to improve a firm's competitive position may not be an appropriate solution to some declining U.S. industries.

Leap-frog type competition also presents pitfalls for an entry with new technology strategy in that other firms will easily bypass entrants later. However, recognizing that critical fixities are necessary evils, the entry with new technology strategy is still viable if the entrants choose the right time to enter. The right time to enter can be determined by modifying equation 7. The issue involved in an entry of this kind is not simply whether to enter the industry, but, more importantly, when to enter. In this case, timing becomes a strategic dimension.

Fifth, the model implies that, other things being equal, a firm should reduce the degree of vertical integration under technological change. Vertical integration lowers the marginal cost and thus increases the critical fixities, leaving the firm less able to cope with technological change. For example, Hays and Abernathy (1978) observed that the U.S. auto industry's vertical integration in cast-iron brake drums delayed its transition to disc brakes by five years.

Sixth, critical fixities, as the model suggests, serve as mobility barriers, a concept proposed by Caves and Porter [1977], between different strategic groups choosing different technologies. As the vintage of technology determines the performance of the firm, technology becomes a critical strategic dimension and could be used to classify firms into different strategic groups. Critical fixities prevent firms of low performance groups from moving to high performance groups which use advanced technologies. Therefore, critical fixities help to explain the formation of strategic groups within an industry as well as the performance differences between these strategic groups.

Seventh, the rate of technological change plays two roles in the replacement decision. On the one hand, the rate of technological change increases the economic gains of delay. Therefore, it serves as an incentive for a firm to wait and extend the life of its existing equipment. On the other hand, technological change decreases the average cost of the new equipment and thus accelerates the replacement process. These two roles interact with each other. The time to replace the equipment, therefore, is when the gains from waiting equal the operating inferiority of the existing equipment.

Finally, this model also provides theoretical underpinnings to the "productivity dilemma" and the "escalating" commitment to the wrong technology. Abnerathy [1978] observed that

> "as productivity increased, significant technological change became more difficult to change......we see that many years of high rates of productivity have come at a cost--a declining capacity for major innovation," (pp. 3-4)

In other words, as capital substitutes for labor, physical labor productivity increases and thus the marginal cost of the existing equipment decreases. As a result, critical fixities increase, and the firm is less interested in adopting technological innovations. Therefore, a cost of productivity growth has less capacity for innovation.

While escalating commitment to previous investments has been interpreted as a psychological phenomenon [Schwenk and Duhaime 1985, Staw 1981], our model argues that, under certain conditions, it is economically legitimate to escalate a firm's commitment to the wrong technology. Once investments are made in an old technology, critical fixities are created. Consider the following scenario: a new technology emerges and is improved, while simultaneously the old technology is also improved. Critical fixities will induce the firm to invest in the improvement of the old technology rather than switch to the new technology even though the new technology is more efficient than the improved old one. Investments in improving the old technology further increase critical fixities, which then induce the firm to commit even more to the old technology. For example, the U.S. steel industry added 48 million tons of Open Hearth (OH) capacity in the 50's, rather than the Basic Oxygen Furnace (BOF) capacity, which was a better technology. Two-thirds of these new capacities were upgraded from the then existing OH shops. Later, in the 60's, steel firms tended to improve the OH shops by adding oxygen lances rather than switch to the BOF (Dilley & McBride, 1967). This escalating commitment phenomenon indicates the importance of choosing the right technology to start with. Once the decision is made, it is difficult to change.

So far, our discussion of critical fixities and their strategic implications has been in general and abstract terms. These implications, however, are useful when describing those industries, such as the steel industry, where the assumptions of the model prevail. Tang [1985] showed that critical fixities could explain, to a certain extent, the innovation adoption behavior, entries and exits, and the performance differences of firms in the steel industry. Taking this work as a starting point, the next section of this paper also uses the steel industry to briefly illustrate the strategic implications discussed above. First, we present an introduction to steelmaking technologies so that the impact of technological innovations on the steel industry can be understood. This introduction is followed by a brief analysis of the dynamics of the U.S. steel industry in terms of the critical fixities model.

THE STEEL INDUSTRY

Steel can be made either from iron ore or from scrap. Steel mills which make steel from iron ore must go through an integrated process: iron making, steel making, casting, and rolling and finishing. These mills are called integrated mills. Other steel mills make steel from scrap by first refining scrap in the Electric arc Furnace (EF) and then rolling or casting liquid steel into the desired shapes.

Since the 1950's, the steel industry has experienced significant changes in each of the steelmaking stages. First, massive cheap iron ore reserves were discovered in Brazil and Australia in the 60's. Second, gigantic blast furnaces were developed in the 60's.[6] Third, the Basic Oxygen Furnace, a steelmaking furnace, was commercialized in 1954 and soon replaced the Open Hearth as the dominant steelmaking technology. Fourth, continuous casting, developed in the late 60's and early 70's, replaced ingot casting as the main casting technology which reduced labor requirements by two-thirds.[7] Finally, in the 60's, the capacity of the EF was enlarged significantly. Since then, it has been economical to produce low carbon steel using the EF at an annual capacity and slightly less than 1 million tons. Mills which use this process are called "minimills," as opposed to large scale integrated mills. Cheap scrap plus the combination of the EF and continuous casting give the minimills a cost advantage over integrated mills.

The U.S. integrated steel sector, however, was slow to adopt technological innovation and to switch to cheap iron ores, thereby losing its domestic and international competitiveness. Our explanation is that since the steel industry is a process technology intensive industry, its decline can be traced to wrong investments made in the 50's, which created critical fixities that prohibited steelmakers from adopting innovations in the subsequent decades.

To evaluate the importance of process innovations to the steel industry, we performed regression analyses on two performance measures against a technology surrogate variable and a variable representing product mix. The two performance measures are profitability measures for the three year averages (1959-1961)[8] of cash flow over gross assests (CFI), and the operating income over net assets (ROI), where cash flow is operating income plus depreciation, and gross assets are net assets plus accumulated depreciation. The technology surrogate variable is the average annual capacity of blast furnaces.[9] This has been chosen as the variable because, historically, integrated steel production has been characterized by significant economies of scale and technological advancements in the steel industry have often been used in upgrading the scale of certain steelmaking equipment (Barnett and Schorich 1983, Boylan 1975, Gold et.al. 1984). The product mix variable, which controls for the effects of potential product mix variables, is steel sheet capacity.[10]

Regression results are given in Table 1, which clearly indicates that process technologies did have an impact on profitability. The coefficients of the BF are significantly different from zero in the two regressions, and the BF scale variable together with a product mix variable can explain over 60 percent of the variation of profitability. These results reveal certain association between a firm's profitability and process technologies. ~~Thus, they illustrate that process innovations could have significant impact on the steel industry.~~ With this in mind, we proceed to use process innovations to explain the structural changes in the steel industry.

Insert Table 1 about here

The U.S. steel industry finished its major expansions in the 50's, during the years when the BOF was in the experimental stage and a decade before cheap iron ores were discovered and continuous casting and gigantic blast furnaces were successfully commercialized. While expanding, U.S. steelmakers used the best technologies available at that time: large blast furnaces capable of producing 1,500 tons of liquid iron per day, large size OHs and ingot casting machines.

In the 1950's, the U.S. steel industry added a 47.8 million ton OH capacity. Also, the blast furnace capacity increased from 71.5 million tons in 1950 to 94.7 million tons in 1959.[11] After adding blast furnaces and OHs, steelmakers continued to add ingot casting facilities. Furthermore, as the U.S. iron ore reserves were almost depleted, the U.S. steel industry vertically integrated backward by acquiring iron ore reserves in Canada [Barnett and Schorsch, 1983]. These new facilities then helped the industry to build its technological superiority in the world and made the U.S. a net steel exporter. But these new facilities and the vertical integrated move resulted in low marginal costs in the following years. These low marginal costs were prohibitive to adopting technological innovations in the 60's.[12] As cheap iron ore was discovered and as top pressured, gigantic blast furnaces, the BOF, large EFs, and continuous casting emerged in the 60's and 70's, the U.S. integrated steel mills were unable to compete with the minimills and the Japanese steelmaking industry which adopted new technologies.

Japan decided to develop her steel industry in 1955, just after the BOF was successfully commercialized. Since 1955, Japan has aggressively expanded her steel industry by adding the most advanced equipment. During the 60's and 70's, the Japanese steel industry experienced the highest growth rate of steel production among major industrial countries. As a result, Japan had the largest and newest steel mills in the world. By 1975, Japanese blast furnaces included six of the world's ten largest. In addition, although Japan did not have any domestic iron ore, she purchased all her iron ores from Brazil and Australia. These ores were cheaper and of a higher grade than the U.S. ores. By adopting the new technologies developed in the 60's and availing themselves of the low labor and low iron ore costs, Japanese steelmakers positioned themselves well as low cost steel producers in the world market. Consequently, Japanese steel easily penetrated the U.S. market.

However, as technological innovations in process equipment become universally available, this entry strategy is easy to imitate. History repeats itself. Now, South Korean and Taiwan steel companies are penetrating the Japanese steel market with the same strategy used by Japanese: low labor cost and new technologies. At this time, Japanese steelmakers are asking for a quota to be set for foreign steel products. Concurrently, Japanese steelmakers also plan to fight back with another generation of casters: strip and plate casters, which save the expensive rolling process. When these casters are available, Korean and Taiwan steelmakers may not be able to adopt them because of the current creation of their own critical fixities.

The U.S. integrated steelmakers are well aware of the development of continuous strip and sheet casters. Given a large stock of ingot casting machines, the U.S. steel industry should be able to bypass continuous slab and bloom casters, and adopt strip and sheet casters in the future. However, continuous strip and sheet casters won't be available for another five to ten years. Given the great inefficiency of ingot casting, it is unlikely that U.S. steelmakers can wait that long without facing certain liquidation. From a strategic point of view, investing in continuous bloom and slab caster now is only a short-term solution with long-term detrimental effects.

Minimills, with new technologies and consequent lower costs, have also gained a significant share of the market which has been traditionally dominated by integrated steelmakers. In 1960, ten or twelve minimills shared about two percent of the market (Miller, 1984). In 1984, fifty minimills shared twenty percent of the total U.S. steel production capacity.

The integrated steel sector was slow to respond to these changes; it simply retrenched. In 1960, there were 53 integrated steel mills; by 1983, only 33 were still in operation. Also, combined accounting losses of the steel industry in the 1982-1984 period exceeded $6 billion. The U.S. integrated steel sector still has probably the least efficient steelmaking equipment in industrial countries.[13]

The above analysis illustrates that there are three distinct strategic groups in the U.S. low carbon steel market: U.S. integrated steelmakers, Japanese integrated steelmakers, and minimills and that critical fixities act as a mobility barrier. It also illustrates that given the relatively high capital and labor costs of the U.S. steel industry, pursuing process innovations will be futile because this strategy creates critical fixities and cannot close the gap of cost differences between the U.S. and Japan. It seems that a strategy of pursuing product innovations is more consistent with the U.S.' strength in technology as well as a more plausible strategy to enhance the U.S. steel industry's international competitiveness.

CONCLUSION

This paper proposed the notion of critical fixities and examined and established theoretical foundations of critical fixities. It discussed some of the strategic implications of critical fixities such as leap-frog type competition, entry with new technology, escalating commitment to the wrong technology, timing of investment as a strategic dimension, lowering vertical integration, and critical fixities as mobility barriers. Critical fixities also explain the productivity dilemma and the coexistence of accounting losses and obsolete technologies. Additionally, this paper used the notion of critical fixities to explain the decline of the U.S. steel industry and the rise and fall of the Japanese steel industry. Specifically, this paper showed how a badly-timed investment in equipment created detrimental critical fixities for the U.S. steel industry, as well as provided theoretical foundations to explain the entry and exit of the steel industry.

This paper is a starting point for potentially useful research efforts. Given that critical fixities are the result of a firm's strategy and that the U.S. economy will rely on technology intensive industries, the determinants of managerial and labor fixities require more research. Additionally, more empirical evidence for the strategic implications of critical fixities is needed in order to make the notion of critical fixities useful when formulating corporate and industrial strategies.

FOOTNOTES

[1] The main reason for making this assumption is to simplify our mathematical formulation.

[2] For example, due to strict work rules, it takes 7 man-hours to produce a ton of steel in unionized Bethlehem steel's Steelton EF shop. This is three times more than the 1.9 man-hours that it takes non-unionized Chapparal Steel's EF shop.

[3] Wall Street Journal, February 10, 1986.

[4] Business Week, May 23, 1983.

[5] This is the inspiration of Charles Schwenk at the University of Illinois, Urbana-Champaign

[6] From the late 50's to the early 70's, maximum daily output of the blast furnace increased six times, from 1,600 tons to over 10,000 tons.

[7] Battelle Memorial Institute [1964].

[8] 1960 was the last year when annual capacities of blast furnaces were reported.

[9] The main reason for choosing the scale of the blast furnaces as the surrogate technology variable is that steelmaking facilities are normally built in consecutive years, and the vintage of the equipment at a particular stage is representative of the vintage of the steel plant. Furthermore, because facilities are built consecutively, high correlations exist between the vintage of different facilities, which pose multicollinearity problems.

[10] Steel strips and sheets are the most expensive low carbon steel products.

[11] American Iron and Steel Institute (AISI), Annual Statistical Report, Washington DC: AISI, 1950-1960.

[12] It is shown in Tang [1985] that either due to low marginal costs or high switching costs, the U.S. steel makers were unwilling to switch to cheap overseas iron ores, gigantic blast furnaces, basic oxygen furnace, and continuous casting.

[13] U.S. Congress, Office of Technology Assessment, Technology and Steel Industry Competitiveness, Washington, D.C.: U.S. Government Printing Office, 1980.

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Table 1

The Effects of Process Technology on a Steel Firm's Profitability

			Coefficients			
Dependent Variable	Constant	Blast Furnace	Sheet&Strip Capacity	R^2	$\bar{R}^2$	Standard Error
		Log(BF)	SSC			
$\frac{\text{Cash Flow}}{\text{Investment}}$ (CFI)	-54.7*	4.61*	8.40**	0.708	0.670	1.86
	(2.38)	(2.53)	(4.01)			
$\frac{\text{Op. Income}}{\text{Investment}}$ (ROI)	-69.5*	5.63*	10.8**	0.651	0.605	2.67
	(-2.09)	(2.15)	(3.57)			

Number of Observations: 18
t-Statistics in parentheses
*Indicates significance beyond the 0.05 level
**Indicates significance beyond the 0.01 level

Definitions of Independent Variables:
Log(BF): Natural logarithm of the average annual capacity of blast furnaces.
SSC: Steel sheet and strip annual capacity as a percentage of total steel products annual capacity.

Source: 1. Moody's Investors Service Inc. Moody's Industrial Manual New York: Moody's Investors Services Inc. 1959-1961.
2. American Iron and Steel Institute (AISI), Directory of Iron and Steel Works of U.S. and Canada, Washington D.C.: AISI 1960.

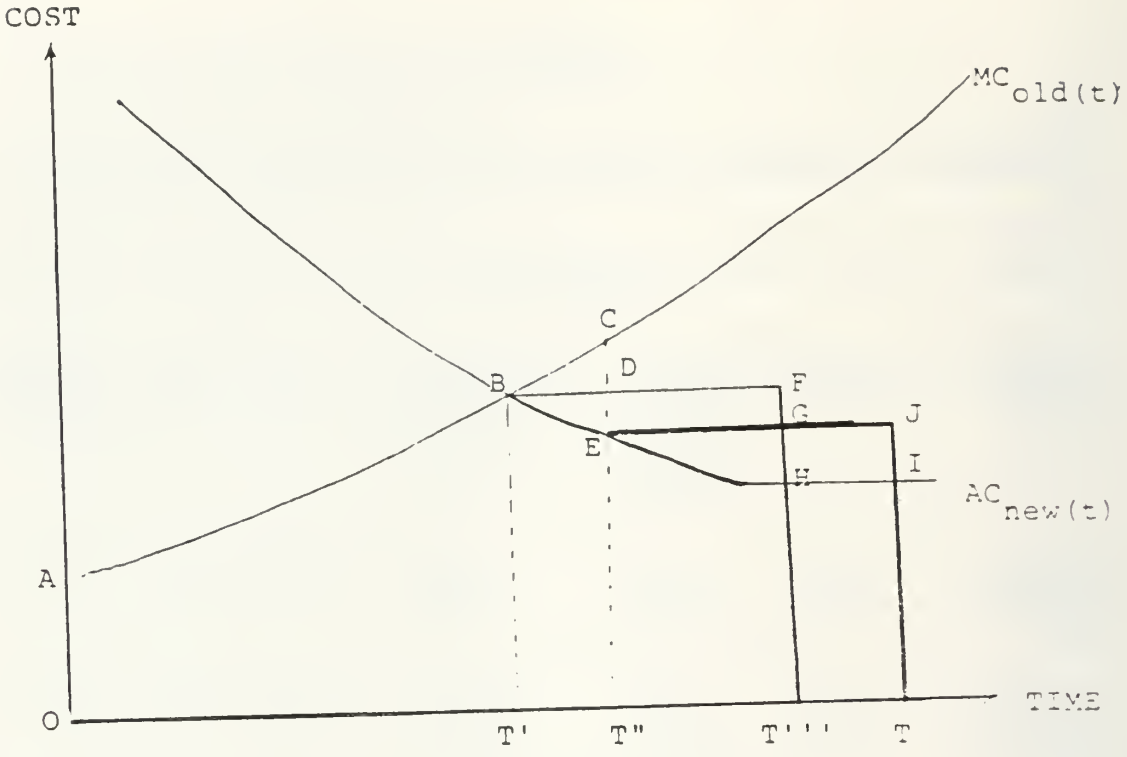

Figure 1 Optimal Timing of Replacement