Understanding the Dynamics of Technology Switching in Seeking to Maintain International Competitiveness

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Abstract

When firms face the possibility of making fundamental change, as opposed to incremental improvements, to maintain their competitiveness, their senior teams face particularly uncertain times. This paper focuses on a system dynamics model that captures the situation of an industry experiencing the switching of its production plants to a new process technology. The model enables the complexity of this situation to be represented, and facilitates a clearer understanding of the expected industry dynamics. The results show that an individual firm facing the up-grade decision must consider the impacts of the change across a number of dimensions, and demonstrates that the point in time along the industry's endemic capacity-building / price cycle may have an important impact on the economics of the decision. The paper is also able to draw some comparisons between this and other approaches to modelling technology change decision-making.

Objectives and Overview

In order to maintain their competitive position, companies must monitor and consider adopting new technologies that will determine the production economics of their manufacturing processes. Incremental technology enhancement may be a continuous process, but some emerging technologies demand fundamental changes to firms' manufacturing processes. Such changes are likely to be costly and disruptive, and so whether to switch to such new technologies and, if so, when become critical decisions. This paper describes a system dynamics model of a technology switching process that aims to provide an executive team with the means for understanding the complex dynamics of switching, investigate critical issues in switch timing, and to gain consensus and gather confidence to face the uncertainties of the change process.

Some models of technology switching in multinational companies have already been developed, but these generally take a single or two time-frame game theoretical approach, often assuming a duopolistic market. The model described in this paper is based on the petrochemicals industry and investigates the dynamics surrounding the diffusion of new manufacturing technology in such a typical commodity product industry. In this case the new technology processes are assumed to be accessible through international licensing agreement or heavy direct investment. The model includes sectors representing an individual firm, and the aggregate of other producers utilising the old and new technologies. It captures the migration of producers from old to new replicating investment appraisal behaviours based on simulated product price and other economic factors. Within this dynamic environment, the model either simulates the company switching when the industry circumstances trigger it, or it may be set to make the change at a specified point in time.

Market dynamics are shown to be complex in such as these essentially oligopolistic industries, where the actions of individual firms in capacity management - building new capacity, "mothballing" and restarting existing plants, and new market entrants/exits - or in changing their production economics can significantly influence supply/demand balances, prices, and critical factors like plant utilisation. The system dynamics approach adopted would appear to offer a much richer understanding of the feedback issues than the game theoretical approaches, and points clearly to the need to frame such technology switching decisions against the expansion/shake-out cycles endemic in such industries.

Technology Innovation and Process Efficiency

All firms strive over time to reduce their manufacturing costs; some savings come progressively and demand relatively little explicit effort and investment, other gains may come from major changes that result from considerable investment and may involve a significant discontinuities in the firm's operations. Martinet (1983) classified advances in operating cost savings coming from three sources:

- Learning - the advantages of which come progressively over time as the firm's experience of the process increases in line with accumulated production and time. Such advances may require little effort and minimal investment (other, perhaps, than in the "debottlenecking" of any rate limiting processes.)
- Size and economies of scale - advantage is predominantly a function of manufacturing/distribution capacity and would be expected to be largely a result of direct investment and a function of enabling technologies.
- Innovation - a firm may make significant advances through the exploitation of process innovation. These might possibly nullify gains made from the other two sources, though this could equally affect the firm's itself, as well as in respect to its competitive position versus other producers.

The last category, which is the focus of attention in this paper, may well involve substantial investment and long lead times in R&D or the external acquisition of technology, careful analysis as to how the change will affect the firm's competitive position regarding price, product quality and so on, and, if existing plant is being up-graded, possible loss of production during the switching process. The dynamic interactions between the dimensions of such technology switching is complex, and the development of a switching strategy in which an executive team can be fully confident is no easy task. Worse still, early ideas of technology innovation (Utterback and Abernathy, 1975) which suggested a model whereby innovation was a key factor in early phases of an industry life-cycle but that gains in the mature phase will only be incremental, are now being challenged. Work, for example, by Tushman and Anderson (1986) on the trends in cement kiln capacities identified major early innovations in the 1890's and then again in 1910. Incremental improvements were then achieved sporadically until 1968 when the Dundee kiln and process control suddenly made kilns of twice the previous maximum size feasible. This new model exposes starkly the complexity of technology development, particularly as it relates to the trade off between the different routes to cost gains, which Clark and DeBresson (1990) also refer to as the "dilemma of efficiency versus innovation". It also highlights that no firms are immune to the impacts of such industry discontinuities.

Texts such as Loverage and Pitt (1990) examine broadly "the *emergent* nature of strategic direction and managerial modes under conditions of transformational uncertainty", but Pitt himself (p.375) asserts that to benefit form the potential benefits of technological innovation "requires the firm to shift unambiguously from an interpretive to an action mode".

Modelling New Technology Adoption

System dynamics has proved itself a valuable tool for investigating the diffusion of technology, though the literature is not extensive and many studies are concerned with product rather than process technology. Maier (1994) and Strohhecker (1994) both report modelling approaches based on the Bass (1969) diffusion model and/or a system dynamics equivalent developed by Milling (1986). Homer (1987) and Paich and Sterman (1993) also report studies involving product diffusion processes. The approach has been applied in the management of IT investment in the health sector (Wing and Maloney, 1994) and in the evaluation of information in an attempt to gauge the potential benefit for IT investment (Clark and Augustine, 1992). It has also been applied widely in the examination of many dimensions change management generally and in business process re-engineering (BPR). Certainly, system dynamics has proved its ability to explain counter-intuitive results through, for example, the work of Kofman et al (1994) whose analysis showed that benefits derived through process improvement like TQM and BPR do not necessary lead to improved bottom line improvement.

Studies that have attempted to capture the adoption of new process technologies have predominantly utilised qualitative models or game theoretical approaches. Game theoretic models are typically based on the Nash equilibrium that maximises utility over the length of the game, and such applications are reported in, for example, Teece (1976) and Conrad and Duchatelet (1987). Georgantzas (1991) developed a differentiated duopoly, two period sequential equilibrium model to examine both offensive and defensive strategies involving technology upgrade options. However this model was not quantified, serving rather to develop a set of scenario outcomes that would, in reality, be dependent on potential payoffs, discount rates and an assumed one-time fixed cost of social transformation and change. Though such models may provide useful characterisations of the dimensions of technology upgrade, their short-comings are clear. The models are rooted in an assumption of the world as a competitive game, usually one-on-one (i.e. a duopoly), rather than as independent firms making separate "locally rational" decisions consistent with their own objectives, amongst which market share may have a greater or lesser priority against required returns for individual investments. Management teams may also be unhappy with models that reduce the sorts of analyses and deliberations they make in the real world to simple mathematical constructs, as has been discussed elsewhere by the author (Winch, 1995).

A Technology Switching Model

This paper now briefly describes a system dynamics model developed to study the dynamics of technology adoption, and goes on to present some early insights arising from its use. The model is based on a sector in the petrochemical industry with an essentially commodity product, and at this stage explicitly represents one manufacturer and the rest of the industry. The industry may be assumed to be in a mature phase, though, as discussed earlier, this does not mean that major technological developments cannot be expected. In such industries, new processes are always possible using extreme operating conditions and/or new catalysts, and indeed radical bio-engineering processes based on recombinant DNA may also offer fundamentally new approaches. In line with many such products the industry is experiencing consistent, if limited, steady state growth in demand, and at least for the purposes on this study does not anticipate any major product substitutions to occur in the foreseeable future. At the commencement of the analysis, the industry utilises a process based on a well established technology, but a new technology has been identified which can offer significant manufacturing cost savings. It is assumed that all firms in the industry would have ready access to the technology through heavy direct investment via licensing or other strategic partnership. (Mowbray, 1992, has drawn on a number of studies to conclude that international technology-related collaborations are an important driving force in industry as R&D costs and risks rise and this is seen as an effective and speedy way to commercialise advances.)

The model was constructed using iThink™, and broadly comprises four sectors which are inter-related as shown in the overview structure in Figure 1.

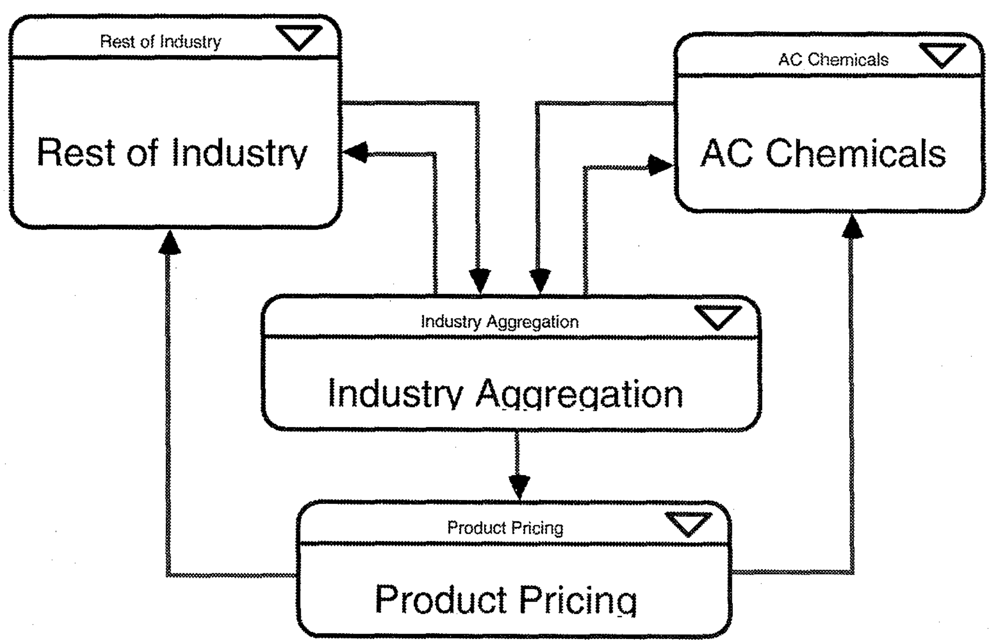

Figure 1 - Overview of Technology Up-grade Model

The sectors, respectively, capture the following key features of industry operations:

1. An individual Competitor, AC Chemicals*. This sector includes elements representing the firm's productive capacity, including the option to upgrade to the new technology, and its process economics. The firm can be allowed to up-grade 'world-scale' sized production units as and when conditions make it propitious, or the model can be set up to trigger the upgrade of all its capacity at any point in time. For the purposes of experimentation at this time, the individual firm is assumed neither to build any new plants nor to shut down any existing plant - only the up-grade option is permitted. At initialisation the firm enjoys a 10% market share.

2. Rest of Industry sector. This sector is identical to the AC Chemicals sector in most respects, but does permit the industry to increase or decrease capacity by building and closing plant. Subsections - 'algorithms' - similar to the up-grade mechanism cause construction and closing of plant as factors like current plant utilisation, profitability (product price), and demand growth dictate. Figure 2 shows the important detail of this sector, and is mirrored for the individual firm. (This sector could be broken out should it be desired to capture the operations of other individual producers, as has been done in other studies, see, e.g., Winch, 1991)

3. Industry Aggregation sector. This sector principally sums all capacity to determine the industry's productive capability; it also calculates the industry weighted average unit manufacturing costs and other metrics.

4. Supply/Demand and Pricing. The model is driven by an external pattern for product demand. Demand is balanced against industry potential supply and impacts on product price. The model reflects that, in reality, capacity under construction as well as that currently operating will have some influence on price - if there is capacity due to come on-stream, then producers may accept lower price in order to capture initial contracts. The model assumes that producers broadly capture sales in proportion to capacity, but also reflects that if and when AC Chemicals has a price advantage or disadvantage against the rest of the industry it may capture more or less sales than its 'share', affecting its capacity utilisation and production economics.

Although the model is not calibrated to represent any particular current situation, its structure and parameters are representative of a typical petrochemical industry and product sector. It is particularly worth noting that the model displays a boom-bust cycle of capacity building then stagnation or shake-out, with a cycle period of around 12-15 years that is entirely typical of petrochemical businesses. Figure 3 shows an example output graph for a run of the base model.

* AC Chemicals is an illustrative fictitious company, and its capacities, operating economics and policies should not be construed as relating to any actual firm.

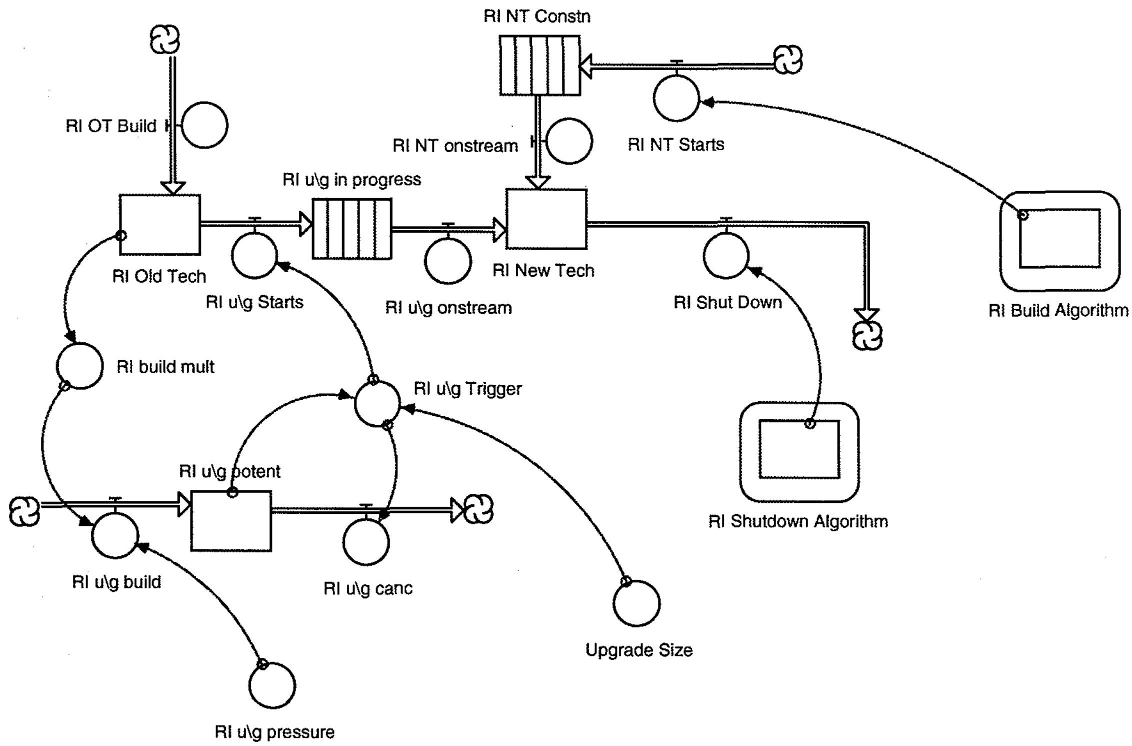

Figure 2 Detail of the Rest of Industry Sector

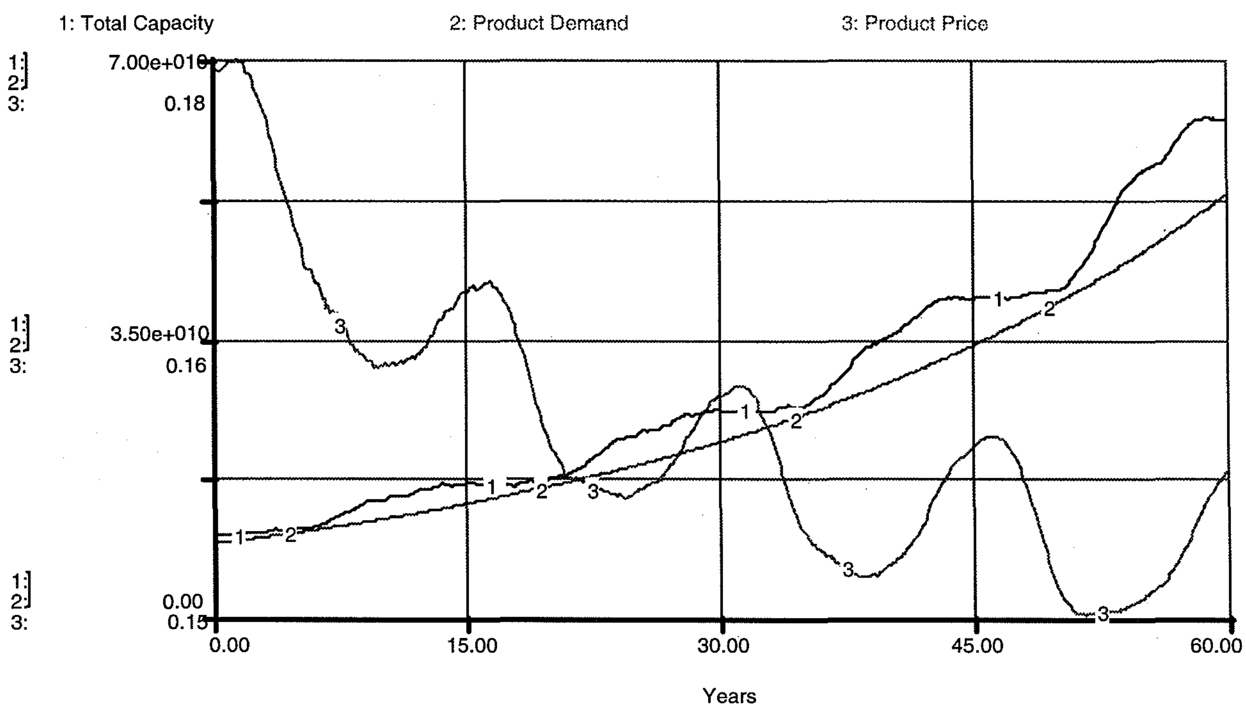

Figure 3 Base run for Technology Up-Grade Model

The input for *Product Demand* shows a steady upward growth of 3% year - typically just ahead of average GDP growth for an industrial economy or region, while the *Total Capacity* displays characteristic cyclical behaviour. The third line represents the pattern for *Product Price*, where all accounting is done in constant dollars. This shows two features - a consistent downward trend as the industry progressively moves over to the new technology, and, in such a competitive environment, manufacturing cost gains are eventually passed on to he customer; and secondly, a cyclical pattern reflecting the capacity building and potential supply/demand cycle.

Results and Discussion

The purpose of model use so far has been to gain a better understanding of the dynamics of technology switching, particularly issues related to timing. Runs have primarily concerned the "triggered" up-grade by the individual firm AC Chemicals, though initially the impact of this strategy was compared with the results obtained if AC were to up-grade over time in discrete packages of "world-scale" size. It should be noted that in this experimentation, the world-scale plant size is kept constant and not expanded as might be possible with further technology advances as discussed in the cement kiln situation earlier.

Impact of AC actions on the Industry

AC Chemicals was set initially to hold a 10% market share in this business it serves, such a level being reasonable for the oligopolistic situation usually pertaining in the petrochemicals industry. The world-scale size of a plant is also set at around 2% of industry capacity at initialisation (implying that AC has five plants or lines). At such levels, it would be expected that any actions by AC would have a noticeable effect on the industry as a whole, though the model contains no specific mechanisms that reflect market leadership or otherwise of the firm. As AC's capacity is held constant, this relative impact would diminish over time.

Figure 4 shows comparative plots for the industry *Total Capacity* in three situations:

1. AC does not expand at all - all opportunities for capacity increases as demand rises are taken up by the rest of the industry
2. AC up-grades its plants or lines progressively as the simulated circumstances dictate.
3. All AC capacity commences up-grade at year 5 of the simulation. The capacity is assumed to be out of commission for approximately one year as the up-grade takes place, and the dip in industry capacity that results is discernible on the plot.

As predicted, AC's actions do indeed have an impact on the whole industry. (Note that this graph, unlike all others, is plotted for only 30 years to increase the detail.) Inevitably the impact is much greater in situation 3 where all AC's capacity is switched in one go - the industry adapting much more readily to gradual change. This plot certainly shows the potential for systems such as these to respond aggressively to stimulation. The dip in capacity as AC's plants undergoes upgrade is sufficient to cause price and industry profitability to rise funding accelerated capacity expansion. Capacity expansion further overshoots on the building boom, but stagnation/shake-out is subsequently longer and delays for around three years the building up-turn in the 18 - 22 year time frame. This is quite consistent with the saying about dynamic systems that "cause and effect are not close in time and space".

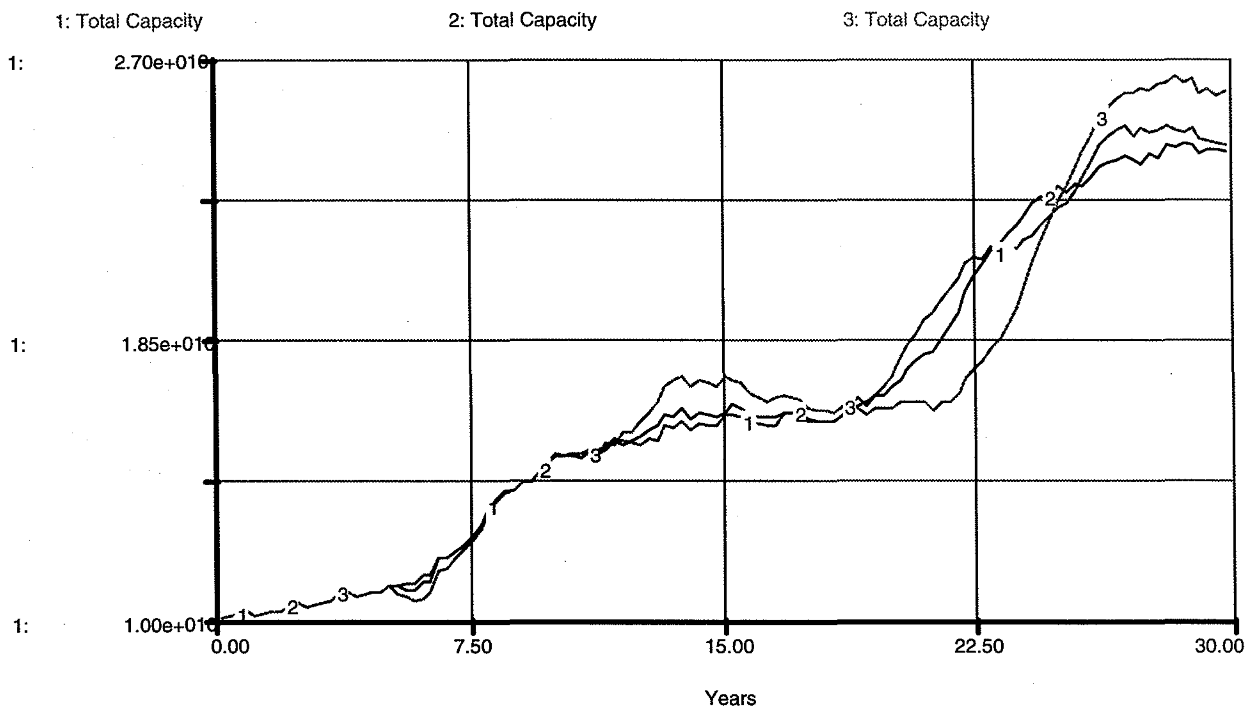

Figure 4 Impact of AC Upgrade Scenarios on Industry Total Capacity

Raising Issues in Competitive Advantage

Should AC decide to upgrade all its plant at a point in time, then the model is parametized to give them a 2¢ improvement in unit costs - Figure 5(a) shows its costs falling from 10¢ to 8¢ as the up-grade is triggered, in this case at year 10. The line for Rest-of-Industry average unit cost can be seen to be declining over time as progressively more plants are up-graded, and as new plants (assumed all new technology) are built. The correlation between rate of reduction in average unit costs and spurts of capacity building can also be seen. Such an output, combined with sensitivity analysis, can contribute to the understanding of timing impacts of competitive (price) advantage and disadvantage that can be experienced during the switching.

Further insights can be gained from Figure 5 (b), which focuses on the relationship between AC's cost differential and its impact on the price it could offer. AC's relative costs and the consequent price it is able to charge relative to the industry are seen to be rising early on as parts of the industry up-grade and new capacity plants are built. The transformation at year 10 is clear, so too is the eventual eroding of the advantage as the rest of the industry continues to switch over to new technology. Review of Figure 5(b), particularly the *AC Offer Price* (line 2), raises important issues concerning the way the AC might use the potential price advantage - should AC drop its price as low as the efficiency gain permits, thereby 'buying' market share and benefiting

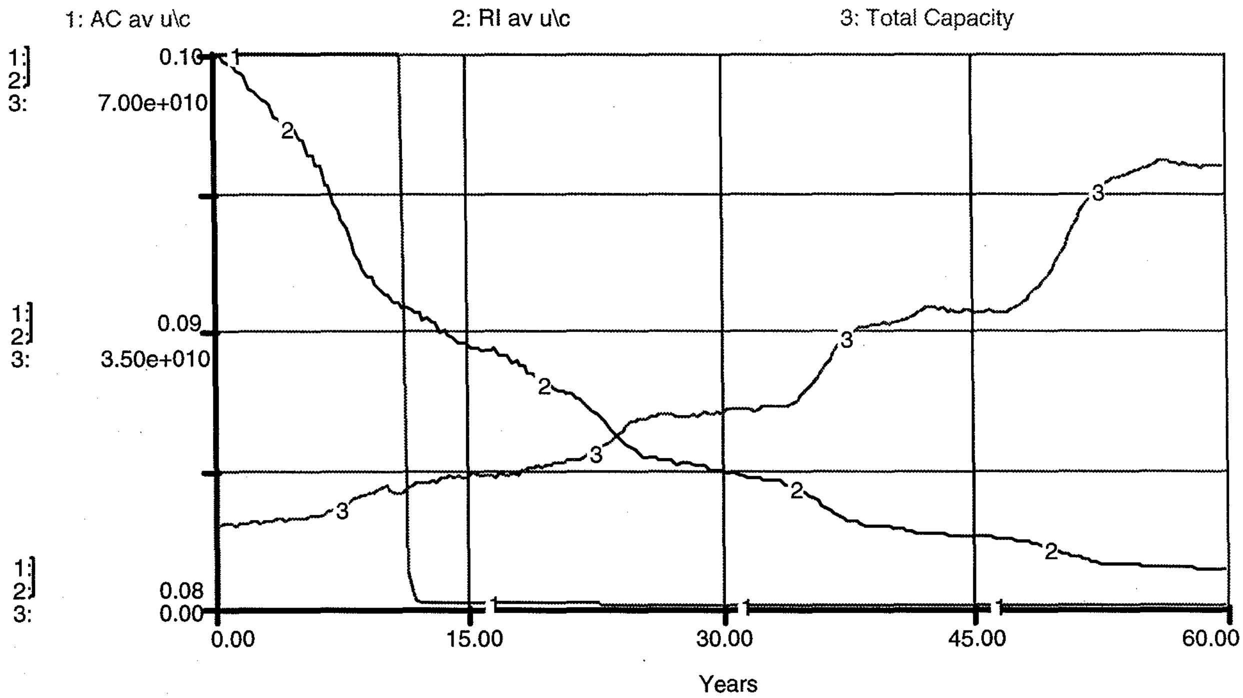

Figure 5(a) AC Cost Reduction and Competitive Response

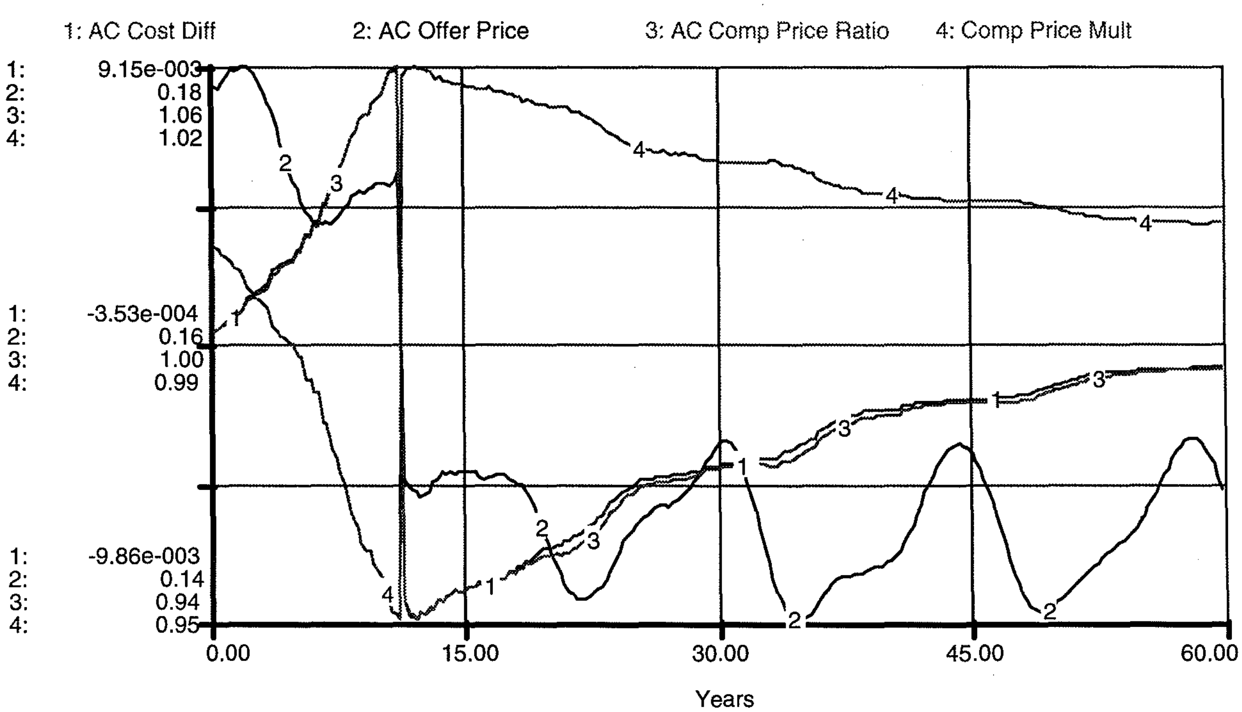

Figure 5(b) AC Pricing Strategy Related to Cost Reduction from volume and utilisation advantages? Should it keep its offer price at or close to the industry norm, maximising margin gain? Or should it pursue some interim or phased pricing strategy. Though not replicated here, there are many scenarios surrounding pricing strategy that can be evaluated.

Up-Grade Timing

As observed earlier, this industry shows a marked cycle in capacity building and consequently in other dependent variables like price and profitability. This does rather beg the question therefore as to whether the up-grade would yield different benefits if it occurred at different points on the cycle. Simulations were performed to examine this issue, by triggering the up-grade at all points between year 5 and year 30. The increase in revenues accruing to AC (against their simulated revenues with no up-grade) were accumulated over the thirty year period following up-grade. Thirty years was considered a reasonable time as it takes in roughly two industry cycles and would be a reasonable plant life-span and investment appraisal time. As the model operates in constant dollars, switching investment costs and discounting factors can be ignored. The industry was also simulated with different patterns of sales sensitivity to AC's offer price differential. The sensitivity patterns assumed are shown in Figure 6(a) - for example with scenario 1 and 10% price advantage would enable AC to increase its sales by around 8%, whereas scenario 3 would give them a 30% boost. the magnitude of such effects was less important for this experiment than whether the price sensitivities had an impact on the timing issue.

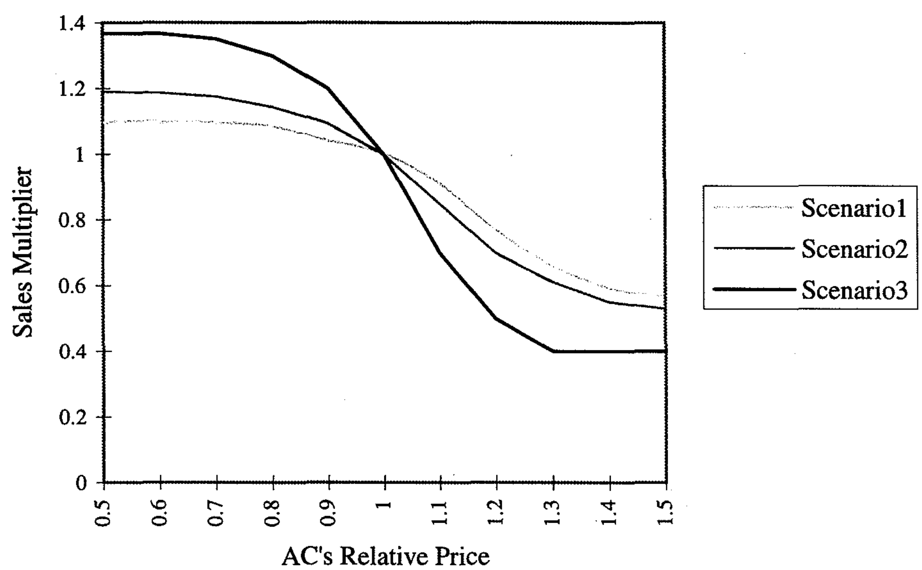

Figure 6(a) Sensitivity of AC's sales to Price Differential

Figure 6(b) shows the relative gains achieved by AC plotted against the year of switch. The results are consistent across all three price sensitivity scenarios with the average gain obviously greatest in the extreme price sensitivity scenario.

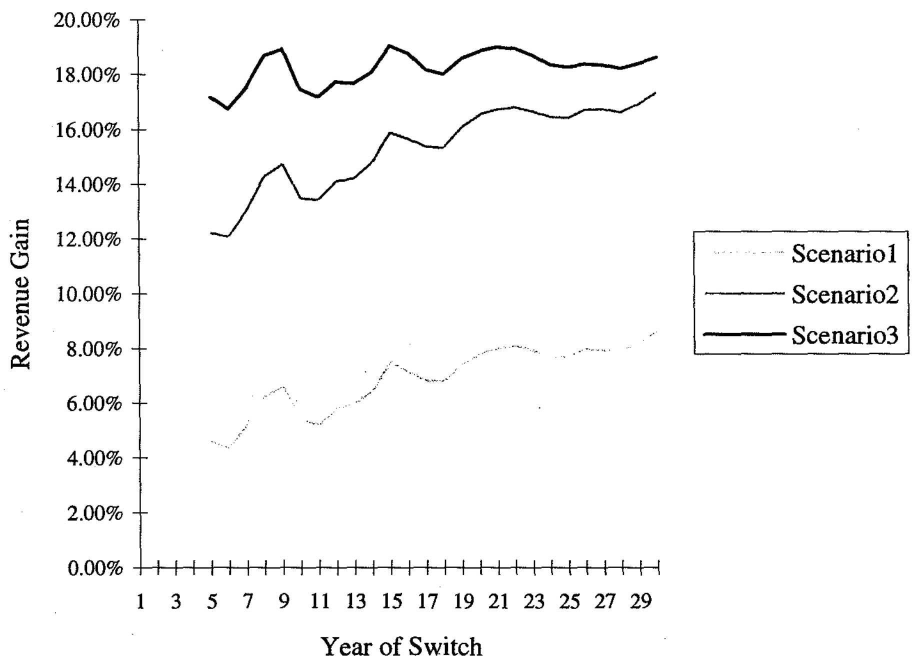

Figure 6(b) Revenue Gains by Switching Technologies

Maximum gains are achieved around years 9, 16, 22, and appear just to be beginning to peak again as year 30 is reached. Reference to one of the plots showing industry capacity cycles shows that years 9 and 22 are around the mid point of the capacity up-swing phase, while years 16 and 30 are about half-way through the stagnation/shake-out phase. On its own this analysis does not yield a definitive answer, it certainly does not suggest that an up-grade decision should be delayed to await an advantageous point, given that during any such delay AC's general competitive position may be being eroded. On the other hand it does emphasise the complexities of up-grade timing, and that there may well be different impacts on the industry which result only from the timing factor. It also points to why circumspection is needed when investment appraisal calculations are being made.

Conclusions

Better understanding of the dynamics of technological change has been called for by Clarke and Howard (1990), including these dimensions:

- A need to unravel the complex patterns by which industry technologies unfold.
- An integration of context and process to understand better how firms' technological positions and strategies develop over time.
- How discontinuities derive from or otherwise amend firm-in-sector competences and the perceptual maps of managers.

This paper has demonstrated the role of models based on the system dynamics approach in contributing to both the context and process of strategy formulation related to technology induced discontinuities. In the specific case of considering whether and when to switch to a new technology process, the analysis has pointed to important issues in progressive versus one-shot up-grade, the use of manufacturing cost gain and competitive (price) advantage, and timing of the up-grade within the industry's endemic cycle. This shows how the approach to modelling technology change delivers a complexity mirroring the real world and a richness of understanding beyond that offered by alternate game theoretical approaches; though it might be argued in response that these such models are much more time-consuming to develop.

The model as described here is essentially intended to serve to aid understanding of the dynamics involved, but can be calibrated to aid an individual firm make a technology switch decision. Further, although it relates to the case of the adoption of a new process within a commodity petrochemical market, the generic structures would relate to other technology changes in other industrial contexts such as the move to CIM, JIT manufacturing, or those process modifications demanded with raw material or sourcing changes.

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