Technological Trajectories and Path Dependence

Luis Araujo
Debbie Harrison
Department of Marketing
The Management School
University of Lancaster
Lancaster LA1 4YX
Phone: 01524 59 39 15
E-mail: L.Araujo@Lancaster.ac.uk
D.J.Harrison@Lancaster.ac.uk

ABSTRACT
This paper is concerned with the notion of path dependence as a framework to understand technological trajectories. The notion of path dependence has been deployed in the economic history and historical sociology literatures to explain sequences of events related mainly to technological and institutional evolution. We adopt a notion of path-dependence that subdivides sequences of events into self-reinforcing and reactive sequences. We further propose that path dependent sequences can be recast in terms of the agency-structure dualism set in a relational-temporal context.

In the second part of the paper, we introduce a case study that illustrates the usefulness of path dependence as a general framework to understand the technological trajectory of the division of a firm involved in a complex change process. Finally, we discuss the implications of using path dependence as a tool to understand change processes in firms and industrial networks.

INTRODUCTION
This paper intends to explore the notion that "history matters" in the evolution of industrial systems. The development of theories of evolution of industrial networks merits a closer examination of the notion of temporality and pattern of connection between events (Aminzade, 1992). Our intention is to rethink the notion of path-dependence in terms of the interplay between action and structure, in which both action and structure embody a variety of temporal orientations.

A simultaneous attention to action and structure highlights the importance of understanding path-dependence not simply from a retrospective perspective but also from an actor-centred standpoint, focusing on how actors react to an uncertain future in real time. Sabel and Zeitlin (1997) mount a critique of path dependence based on its insensitivity to the situated reflexivity of actors who, faced with critical choices, may adopt a variety of coping strategies rather than being forced into commitments that may be difficult to reverse.

The structure of the paper is as follows: in the first part we will survey current uses of the notion of path dependence in the economic history and historical sociology literatures. Our argument is that the notion of path dependence is best understood as a general framework to understand how temporal-relational contexts of action are formed and how specific events can contribute to their reproduction or transformation. In the second part of the paper, we

introduce a case study that illustrates the use of path dependence to chart the evolution of a technology. In the final part of the paper we will suggest some conclusions and implications from our study.

A BRIEF REVIEW OF THE PATH-DEPENDENCE LITERATURE

The notion of path-dependence has been deployed within the industrial networks literature largely to account for the stability and change of technological systems (Lundgren, 1995; Håkansson and Lundgren, 1997; Håkansson and Waluzewski, 1999). Håkansson and Lundgren (1997) provide the most comprehensive review of the topic from an industrial networks perspective. In this paper we wish to build on this contribution by recasting the notion of path dependence in a relational-temporal context.

The notion of path-dependence in the social sciences has largely been developed by economists concerned with the evolution of technology and institutions and has partly served as a platform to reinstate "history" back into economic theory. The best known representative of this new brand of economic history, sensitive to both historical singularities and systematic generalisations, is David's (1985) story of the emergence and persistence of the QWERTY keyboard.

The pioneering influence of Arthur (1989, 1994) and David (1985, 1988) on the economics of technology was later mimicked in institutional economics most notably through the work of Douglass North (1991). Magnusson and Ottosson (1997) contain a number of surveys on the evolution of technologies and institutions from a path dependence perspective[10]. The definition of path-dependence adopted by David (1985:332) was:

"A path-dependent sequence of economic changes is one of which important influences upon the eventual outcome can be exerted by temporally remote events, including happenings dominated by chance elements rather than systematic forces. Stochastic processes like that do not converge automatically to a fixed-point distribution of outcomes, and are called non-ergodic."

This definition highlights two important issues. First, path dependence is a property of sequences of events, in which a particular process is unable to shake free from the influence of its past states or motions (David, 1988). Secondly, path dependent processes combine general processes with processes that are unique and unpredictable, merging necessity and chance in the same sequence.

Antonelli (1997) makes a useful distinction between past and path dependence using simple and complex Markov chains. If events within a specific system at an arbitrary time ***t***, can be predicted on the basis of the state of the system at time ***t-1*** – independently of how the system arrived at time ***t-1*** – then we are referring to past rather than path dependent processes.

By contrast, if the probability of transition of a system from state ***t-1*** to ***t*** is dependent not only on the state of the system at ***t-1*** but also on the transitions between previous states (***t-2,...,t-n***), processes are non-ergodic and fully path dependent. In path dependent processes, agents are assumed to be "state dependent" and yet still be able to generate structural changes

[10] See also the special issue on path dependence of the *International Journal of Industrial Organization* Vol. 15, 1997.

and modify the behaviour of the system in unpredictable ways either intentionally or indirectly via the unintended consequences of aggregate actions. [11]

Path dependent sequences require explanation as to how the systematic and contingent association between sequences of events comes about. In explaining path dependent sequences, we are thus forced to dig deeper into the causal mechanisms that account for the sequential and logical association between events (Goldstone 1998; Haydu, 1998).

Path dependence arguments suggest that there is more to the world than patterns of events. The world has ontological depth. Events are the products of mechanisms that derive from the properties of objects acting in specific spatio-temporal contexts. Furthermore, there is an "out-of-phaseness" between the operation of causal mechanisms and the effects they produce (Sayer 2000:15). The asynchrony between causal mechanisms and their effects invokes a spatial and temporal spread of causes. In particular, current events bear the imprint of past events through the operation of social and material structures that act as the "carriers of history".

The notion that current events may have remote temporal causes means that the present is past but not necessarily path dependent. Past dependence is pervasive and inevitable, path dependence is not. The notion of path dependence means more than past-dependence or saying that yesterday's choices, embodied in durable structures (e.g. technologies, institutions), are the initial point for today's choices. Path dependence signifies that the ordering in which things happen affect their sequence and temporal unfolding. And, the operation of agency at a particular point in time may activate a whole series of further and connected options as well as foreclose other possible alternatives (Tilly, 1994).

The notion of path dependence does not imply that the future is in any way closed. The notion that events can have remote temporal causes does not amount to saying that they are predetermined. Social systems are open systems and the operation of causal mechanisms is contingent upon certain contextual conditions – namely on the spatial and temporal relations with other causal mechanisms that may trigger, block or modify its actions and produce different outcomes on different occasions (Sayer 2000: 15). There is thus nothing inevitable about specific sequences of events; events could often and easily have turned out otherwise.

Mahoney (1999) surveys the use of path dependence in historical sociology and identifies two different streams of uses of the notion. The two uses of path dependence focus on self-reinforcing and reactive sequences of events. During self-reinforcing sequences the analysis focus on the mechanisms that reproduces patterns of events over time – the mechanisms that keep "history on track" (Haydu 1998: 353). This type of analysis often focuses on both the contingent, path shaping conjunctures that switch events on to particular tracks as well as the mechanisms that lock-in subsequent events to a particular trajectory. By contrast, in reactive

[11] The role of path dependence in economic processes is the subject of some controversy in the economics literature. On one hand, the opponents of path dependence regard it as no more than a way of stating that history matters or that decisions taken today have durable consequences whose effects cannot be predicted in advance (Liebowitz and Margolis, 1995). The thrust of this critique seems to be on the notion of whether or not outcomes of historical processes are efficient (e.g . QWERTY keyboards) and if they are inefficient, whether they can be remedied *ex-ante*. David (1997) rebuts these criticisms and disentangles the contingent association between path dependent and inefficient outcomes of evolutionary processes.

sequences initial events trigger a sequence of tightly linked reactions in which the initial move rather than being reinforced over time, moves the system to new paths.

Historical sociologists, like economic historians, often focus on conjunctures arising from the temporal intersection of different trajectories. At these conjunctures, actions can become highly consequential and the possibilities for rearticulating structures arises, whether or not agents are aware of the efficaciousness of their actions (Aminzade 1992: 467). Porac (1997) describes how the DOS transaction between IBM and Microsoft turned out to be a conjuncture of two autonomous trajectories that shaped the future of the PC market in ways that none of the parties involved in the transaction could have foreseen.

Another way to conceptualise these notions is to recast them in terms of trajectories and turning points (Abbott, 1997). Trajectories are interlocked and interdependent sequences of events whereas turning points are events that have the potential to redirect trajectories along new paths. Trajectories have thus an inertial character, coercing processes within along predetermined paths and their ability to absorb minor variations and ruptures in processes without any appreciable impact on the overall direction of the trajectory (Sewell, 1996). Turning points are more consequential than trajectories since they switch trajectories to new paths.

Abbott (1997) remarks that a choice is made in relation to an uncertain future and not always in the knowledge of whether or not the choice is likely to be a turning point. A choice is not an isolated act detached from the structures in which those choices are framed and exercised. Agents experience and understand their worlds in interaction with others, in the network of relationships that sustain those interactions (Lane et al, 1996). These network of relationships establish enduring patterns of connections that reappear at the next iteration of the process (Abbott 1997: 99) The past is thus encoded in the present, in these patterns of connections that Abbott refers to as structures.

This perspective on path dependent sequences leads us to a closer scrutiny of the agency-structure dualism and their interplay in a relational and temporal context. The agency-structure dualism has been the subject of a long debate in sociology and need not detain us here.[12] Our purpose here is to highlight the fact that structures, rather than forming an overarching set of constraints, have an inherent spatial and temporal component. As Jessop (forthcoming) argues, given structures may privilege some spatial and temporal horizons, some structural positions and strategies over others. And, actors (individual or collective) through strategic and reflexive actions are able to take advantage of this differential privileging of structures when choosing a particular course of action. Two other implications follow from this view. First, structures exist at different levels, are differentially connected to each other, and may afford different sets of opportunities and constraints. Secondly, agency is not only differentially distributed (i.e. it is contingent upon structural position) but also may be more or less efficacious at different times.

In the industrial networks approach connections between three levels (actors, resources and activities) form structures that are variably interlocked with one another and embody different temporal orientations (Håkansson and Lundgren, 1997). For example, changes at the actor level (e.g. an actor is replaced in a dyadic relationship) often occur without a significant impact at the level of activity structures or resource constellations. Typically, resource

[12] See for example, Giddens (1984) and the critique of Sewell (1992).

structures embody a different temporal orientation than activity or actor structures. Resources are partly defined by their durability, and their ability to be reused in the future (Easton and Araujo, 1996).

As Sewell (1996) notes, it is because structures exist at multiple levels and are variably articulated with each other, that localised ruptures have the potential to bring about a cascading series of other changes that in turn lead to structural transformations. More often than not, a single isolated rupture does not tear the fabric of structures, and results in either the reproduction of the same structures, or incremental and localised changes. However, ruptures may spiral into a sequence of interrelated ruptures that disarticulate existing structures and provides opportunities for novel rearticulations.

In the economic history approach to path dependence the types of structures that are of interest are those related to technologies and institutions. Arthur (1994: 112) identifies four sources of self-reinforcing mechanisms in economics: large set-up or fixed costs (which give the advantage of falling unit costs to increased output); learning effects (which act to improve products or lower their costs as their prevalence increases); coordination effects (which confer advantages to "going along" with other economic agents taking similar action); and adaptive expectations (where increased prevalence enhances beliefs of further prevalence).

For David (1994), as for other institutional economists (North, 1991), the emergence of institutions is seen as a response to uncertainty and the notion of "carriers of history" is used to account for their evolution. The "carriers of history" can be grouped in three categories. First, institutions serve the purpose of establishing mutually consistent expectations and conventions that enable coordination in a decentralised system. Secondly, organisations such as business firms develop informational channels and codes that facilitate internal communication, and constitute an idiosyncratic form of organisational capital. Finally, institutions evolve complex interdependencies and complementarities amongst their constituent elements, with the attendant implication that changes in one dimension often have consequences elsewhere.

Sabel and Zeitlin's (1997) critique the notion of path-dependence for focusing only on self-reinforcing mechanisms and neglecting reflexivity – i.e. the ability of actors immersed in particular trajectories to observe the results of their own actions and deliberately try to change the conditions in which they find themselves. In this critique path dependence is associated with fatalism; once locked in a particular trajectory, actors have no choice but to be carried along the paths that self-reinforcing mechanisms have shaped for them.

Jessop (forthcoming) suggests that path dependence, whilst limiting current options, does not imply fatalism. Strategically reflexive, temporally oriented actors can make sense of their own position, interests and identities, alter the direction of the paths they follow or shape new paths altogether. In summary, actors can be seen as fusing together and redefining past and future in their moment-to-moment choices and decisions (Sabel and Zeitlin 1997: 29).

Emirbayer and Mische (1998) propose a temporally oriented definition of agency that allows us to elaborate on the notion of strategic reflexivity of actors. Agency according to Emirbayer and Mische (1998: 970) is: " …the temporally constructed engagement by actors of different structural environments – the temporal-relational contexts of action – which, through the interplay of habit, imagination and judgement both reproduces and transforms those structures in interactive response to the problems posed by changing historical situations".

Emirbayer and Mische (1998: 971) distinguish three different temporally oriented components that make up agency: an iterational component, a projective component and a practical-evaluative component. The iterational element refers to the selective reactivation of past patterns of thought and action as routinely incorporated in practice. The projective element denotes the imaginative generation of future scenarios and trajectories of action in relation to actors' hopes, fears and desires for the future. Lastly, the practical-evaluative element refers to the capacity of actors to make practical and normative judgements among alternative trajectories of action in response to emerging demands, opportunities and ambiguities of presently evolving situations.

This temporally oriented definition of agency reinforces the notion that actors have always got a foot on the past, the present and the future. They adjust their temporal orientations in relation to changing circumstances in more or less reflective or imaginative ways. They selectively engage with routines and habits from the past, evaluate present possibilities and project hypothetical new paths into the future. Their temporal orientation may also change in response to specific circumstances (e.g. more past or future oriented) and structural contexts.

In summary, the notion of path dependence requires a temporally oriented notion of structures and agency. The agency–structure dualism recast in a temporal context allows us to account for the self-reinforcing as well as the reactive sequences of events. In particular, a temporally sensitive notion of agency underscores the fact that actors are products, but not prisoners of their own histories.

In the following section, we present a longitudinal case study focusing on the evolution of a division of ICI[13] involved in a discontinuous technological change, relating to the replacement of CFCs[14]. This case is described at length in Harrison (1998). In the first part, we use a periodised narrative to describe a series of events that drove this division of ICI to embark on a particular technological and market trajectory. In the second part, we use path dependence focusing on turning points and self-reinforcing sequences to account for the periodised narrative described earlier. We will also attempt to highlight the extent to which actors were aware of and reflected on the consequences of their actions, on them as they confronted a series of emerging problems and choices.

Case: ICI and the replacement of CFCs

At ICI the production of a range of CFCs began in the late 1950s. ICI also has an HCFC[15] business, centred on HCFC-22, which started in the 1970s. The CFC business "...was often the most profitable business within Chemicals and Polymers" [16]. ICI had a 10% share of the worldwide CFC market. ICI is also the main producer of CFC alternatives in the UK. The banning of CFCs was regarded as an opportunity for ICI to change their market position substantially. "

Period One - Early Atmospheric Research (1960s - 1974)

In 1972 a seminar on the ecology of fluorocarbons took place in the US. The seminar was organised by Dr. R. McCarthy of DuPont, and representatives from all of the worldwide CFC

[13] KLEA is the name of the division of ICI concerned with fluorocarbon alternatives business
[14] CFCs stands for chlorofluorocarbons
[15] HCFCs stands for hydrochlorofluorocarbons
[16] Interview with Andrew Elphick, Sales Manager, ICI KLEA, March 1996

producers were invited. Du Pont was in a leadership position and took a leading role in mobilising industry concerns.

Period Two - The Fluorocarbon Link (1974 - 1980)
The debate over the possible role of CFCs in ozone depletion was believed to have started in earnest in 1974. The publication of the Rowland and Molina hypothesis was said to represent a "...dramatic change..."[17]. It was recognised that, should this hypothesis be true, then there would be very serious consequences to the business.

An in-house search for alternatives started during 1974-75, and lasted for four years. This "...just in case" [18] stance was felt to be sensible as "...a precautionary look at what the alternatives might be if we ever had to get into alternatives" [19]. By 1980 two possibilities emerged from the search: HCFC-123 and HFC-134a[20]. HCFCs and HFCs were considered to be a long-term alternatives to CFCs. However, there were substantial barriers to further development in the existing context. Both of the new chemicals were more difficult and expensive to make when compared to CFCs. In addition, at the time there was little interest on the part of customers. Hence, there was little incentive to invest in (expensive) toxicology testing, the next stage of development.

Period Three - Natural Correction (1980 - 1985)
A loss of momentum was perceived by managers as the issue "...largely disappeared from the agenda..."[21] of government, environmental groups, and industry. The mainstream scientific community consensus was that there was a natural cycle of ozone creation and depletion. The halting of activity was viewed as a sensible response and "...at that point work really ceased and was put on the shelf" [22]. For ICI it was now a case of "business as usual".

Period Four - Evidence of Ozone Depletion (1985 - 1987)
The discovery of the 'ozone hole' in 1985 was considered to have "...changed everything...the 'hole' was a reality, whatever was causing it" [23]. Afterwards the Vienna Convention for the Protection of the Ozone Layer was established. Managers "...dusted off the files...this one is coming back again..." [24].

At the industry level, the Fluorocarbon Program Panel (FPP) increased the funding available for scientific activity. The industry position was that there was still insufficient weight of evidence for action. These pre-competitive actions were central to the later in-house response.

At the company level, managers started to consider a post-CFC market position. "We want to be ahead of that change, we want to actually be ready for the change when it comes…" [25]. The re-opening of research into alternatives occurred in March 1986. HCFC-123 and HFC-134a were considered to be the two most promising chemicals that emerged from the 1970s evaluation.

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[17] Interview with Mike Harris, External Affairs Manager, ICI KLEA, January1996
[18] ibid.
[19] ibid.
[20] HFCs stands for hydrofluorocarbons
[21] ibid.
[22] ibid.
[23] ibid.
[24] Interview with Mike Harris, External Affairs Manager, ICI KLEA, January 1996
[25] ibid.

While the alternatives programme was underway, there was a deliberate market shift from aerosols to refrigeration and air conditioning. In early 1986 the belief within ICI was that CFCs were probably to be regulated in some way, though the possibility of a ban was "...not part of the debate"[26]. Managers considered that "...the thing that regulations would do would be to encourage people to change" [27].

From this view two scenarios were formed. The first of these was that there was a need for ICI's aerosol customers to change rapidly, even if CFCs were not eliminated. ICI was powerless to arrest any sustained movement to hydrocarbon technology. Attention then moved to considering the shape of the business without the aerosol sector. A decision was taken to select a market where the alternatives available were unclear, that of refrigeration.

There was a need for development in a number of areas. First, the existing CFC business had a small geographic spread with market strengths in "traditional imperial ICI geography" [28] areas. ICI's market presence in Europe, Asia and particularly North America (where the majority of sales of the alternative would be) was weak. Second, the skill base of the division was focused around aerosols. Third, the marketing structures had to be radically changed. Lastly, the ICI group had an internationalisation strategy during the 1980s, whereby "...business decisions had to present themselves to the central Board as a global business" [29].

Period Five - Agreement of Montreal Protocol (1987 -1989)

The Montreal Protocol was agreed in September 1987. Soon afterwards, two significant scientific discoveries "...changed everything" [30]. These were the discovery of the "Northern hole" and the results of the Airborne Stratospheric Arctic Expedition; CFCs were conclusively cited as the predominant cause of ozone depletion.

Industry completely changed its stance during 1988, and many of the producers called for a ban of CFCs. Both the changed scientific context and the agreement of the Montreal Protocol "...increased the certainty as much as possible before we made major investments" [31]. It was now assumed that the CFC business would be lost, and that a huge investment in a new business was now necessary to survive. The present requirements of the Protocol were felt to allow ample time for the commercial development of alternatives.

In early 1988 ICI learned that the US automotive industry were keen to move quickly. This was due to the nature of their product; vehicles had to be serviceable. At this stage ICI had very little presence in either the US or in air conditioning, "...but we needed to be..." [32]. This market was important because of the large volumes involved. ICI then realised that the US auto industry wanted a replacement by 1992 - in five years time. The auto manufacturers were reasonably confident that they wanted HFC-134a as the CFC replacement.

Managers then made "big decisions, which was we are going to go for this because we actually think that here is a commercial opportunity for us to apply what we do well which, is

[26] Interview with Tom Crotty, Sales Director, ICI KLEA, January 1996
[27] ibid.
[28] ibid.
[29] Interview with Andrew Elphick, Sales Manager, ICI KLEA, March 1996
[30] Interview with Mike Harris, External Affairs Manager, ICI KLEA, January 1996
[31] ibid.
[32] ibid.

the translation of difficult chemistry into large-scale production facilities very fast. We were looking at a very, very, accelerated time scale...with customers telling us that they wanted to buy large quantities of a product that currently existed in a test tube...in four years time." [33].

The commercial development programme was perceived as "...a very fast track process of product and process development...we moved at fantastic speed by our own standards, and I would suggest by external standards too" [34]. The first plant was being built at the same time as the product technology was being developed! Investments in three production facilities (one each in the UK, US, and Japan) occurred between 1988 and 1993. Technology, plant, and process development overlapped substantially during the crisis period. All three of the plants were to produce HFC-134a.

Period Six - Tightening of Protocol requirements (1989 - 1992)
With the HFC-134a programme underway in 1989, the ICI Fluorocarbons board took a decision not to invest in any new HCFC alternatives. It was predicted that regulations around CFCs would move forward each time because of new scientific evidence. An assumption was made that the same process would occur with regard to HCFCs. Therefore "...the economic payback on investing in HCFCs wouldn't be that good...we would focus our resources on investing in totally non-ozone depleting alternatives" [35]. This stance preceded any regulatory dates for the control of HCFCs.

By mid 1991 the belief was that "...the die was cast" [36]. There was now a decision for the planned expansion of what was currently a one-product division. ICI started to prepare for future demand for ozone friendly alternatives to HCFC-22. There were no obvious replacements, and no prior experience of any of the options. "...We came to a view...that...we would have to make blends...in order to meet that need. And we identified that the blends would be combinations of three HFCs" [37]. ICI built the world's first HFC-32 plant in the UK during 1992.

The decision to 'jump a technology' by concentrating upon HFCs (rather than HCFCs) is now considered to be the wrong one: "... the fact that they [HCFC regulations] haven't been brought closer through the Protocol...has destroyed forecasts of a global business by the year 2000. Instead the business will not meet these [targets] until 2015...there have been enormous opportunities which have been missed..." [38]. In hindsight ICI should have moved back from "...mission impossible..." [39] earlier, in that the waning commitment of governments had been misread.

ICI's forecasts have been affected by a number of interrelated features. Controls for the banning of HCFCs by 2015, introduced under the Copenhagen round in 1992, have not been revised as ICI expected. In the early 1990s a massive capacity for HFC-134a came on-line as the producer industry built new plants within a similar time period. One impact of this capacity availability was to reduce prices to below forecasts. This was also affected by the patterns of adoption of alternatives by the user sectors. Several have switched to the use of

[33] Interview with Tom Crotty, Sales Director, ICI KLEA, January 1996
[34] Interview with Mike Harris, External Affairs Manager, ICI KLEA, January 1996
[35] Interview with Mike Harris, External Affairs Manager, ICI KLEA, January 1996
[36] Interview with Tom Crotty, Sales Director, ICI KLEA, January 1996
[37] ibid.
[38] ibid.
[39] ibid.

HCFCs because in many cases it is a drop-in technology. Further, other user sectors have switched to NIK technologies[40], reducing the size of the CFC replacement market.

CASE ANALYSIS

This case illustrates a number of issues raised in the first part of this paper. We want to focus the analysis on two interrelated questions: how can the sequence of events be understood from a path dependence perspective?; to what extent were the actors involved aware of the consequences of their choices, and particularly, of the lock-in effects of the actions they undertook?

In relation to the first question, the periodisation we adopted earlier focuses mainly on conjunctures within the trajectory of ICI evolving alongside other trajectories, related to CFC replacement. These are scientific knowledge on the effects of CFCs on ozone depletion, the regulatory framework; market concerns across a number of end-user industries; and finally, the industry-wide response to the unfolding events. These trajectories evolved in parallel, were embedded in structures with their own temporal orientations, and their coupling varied over time (see table one).

For example, the initial in-house development of CFC alternatives at ICI proceeded any conclusive scientific evidence concerning the depletion of the ozone layer or any regulatory framework advising the phasing out of CFCs. The results of the initial development phase were shelved until years later, when scientific evidence and the establishment of the Vienna Convention resurrected a potential issue. By the time the Montreal Protocol and conclusive scientific evidence led to industry calls for the ban of CFCs, ICI had already made definitive plans for focusing development, production, and marketing resources to the global refrigeration market.

The later decision to move rapidly into the full scale development and production of HFC-134a as a CFC replacement for the US auto industry could be seen as a critical juncture, arising out of the confluence of a number of interrelated trajectories. First, ICI's initial development work in the 1974-80 had established HFC-134a as a viable CFC replacement. The selection of the refrigeration market and the move away from the aerosol market, as well as the marketing investments in three main markets (Europe, North America, and Japan), had paved the way for further investments in HFC-134a. The perception of the effects of the Montreal Protocol on future demands for CFC alternatives lent further urgency and legitimacy for pursuing the HFC-134a route. And the interest of US auto industry for the early availability of a CFC alternative for air conditioning equipment further tipped the scales in favouring a speedy commitment to moving from test-tube chemistry to production plant engineering.

In summary, the decision to build three plants for the pursuit of a global HFC134-a business focused on the refrigeration industry has to be understood in the context of a complex trajectory that can be characterised as a path dependent sequence. The order in which events happened affected their sequence and their subsequent trajectory. For example, the initial research into CFC alternatives and the decision to move away from aerosols and into refrigeration partly shaped the decision to focus on the HFC-134a global market. The decision to move swiftly and decisively into the HFC-134a alternative, with a record time

[40] NIK : not-in-kind or non-fluorocarbon technologies, -e.g. hydrocarbons, water-based cleaning.

scale for the move from development to production, not only committed ICI to a self-reinforcing trajectory; this also foreclosed the pursuit of other alternatives. When later it came to finding replacements for HCFCs, its previous trajectory and the resource infrastructure it had built for producing HFC-134a shaped ICI's approach.

To what extent did ICI's managers perceived the trajectory of the company's response to be path dependent, and how reflexive were they about critical junctures and path shaping decisions? This case illustrates a difficult to reverse commitment to what in hindsight turned out to be the "wrong" course of action.

There is little doubt that the commitment to move into the production of HFC-134a was regarded by ICI as a path shaping decision and one that would be costly and difficult to reverse. This decision illustrates well how choice situations can be framed in terms of a fusion of the past, present, and future. We have already highlighted how the decision to move into HFC-134a was partly the product of past decisions and commitments. More importantly, this decision illustrates how a clear projection of the future shaped not only the size, but also the speed of the commitment ICI undertook. A belief in the company's capabilities into the translation of laboratory chemistry into large-scale production and the belief that customers wanted to buy a product that only existed in the test-tube four years down the line, accounted for the speed of commitment ("mission impossible"). In hindsight the company wished it had not embarked on this course of action but by then the "die was cast". ICI had little choice but to contend with how best to capitalise on the opportunities afforded by the path it had embarked on.

CONCLUSIONS

The main argument of this paper is that the notion of path-dependence provides a useful platform to understand stability and change in the trajectories of firms and technologies embedded in complex industrial networks. We have adopted Mahoney's (1999) proposal that path dependence sequences be subdivided into periods of self-reinforcing and reactive sequences. Self-reinforcing sequences are dominated by structural mechanisms, often remote in terms of their spatial and temporal origins that keep "events on track". Reactive sequences are characterised by consequential, path shaping actions that often rearticulate existing structures and move events into novel paths.

The ICI case has illustrated both how self-reinforcing sequences and critical junctures can account for a particular trajectory. As we have seen, the response of ICI to the eventual phasing out of CFCs was a product of a complex and multi-faceted series of events that acted in concert to lock the company in a particular technological and market trajectory. In particular, we showed how the decision to move ahead with a crash programme designed to build a HFC-134a global market for refrigeration applications could only be understood as both the product of ICI's history in CFCs and its intersection with other related trajectories.

A focus on path dependence has thus a number of implications for the study of stability and change from an industrial networks perspective. First, path dependence highlights how sequences of events combine both systematic and contingent causes. Events and event sequences are often the product of causal mechanisms related to deeper structures that "carry history" forward in the form of technological solutions, rules of conduct, etc. But socio-economic systems are open systems, populated by strategic-reflexive actors involved in both the reproduction and transformation of structures in which they are embedded. The operation

of causal mechanisms is always contingent on their spatial and temporal relationships with other mechanisms that may transform or subvert trajectories. The ability of actors to engage in reflexive narratives of their own trajectories and their ability to act on envisioned futures introduces a degree of contingency and openness about the future.

Secondly, if "history matters", both actors and analysts have to be clear in how it matters and through what mechanisms is history being carried forward. And, rather than regarding the weight of history simply as a constraint on what can be done, we need to be sensitive to the enabling side of the past. As Håkansson and Waluzewski (1999) have shown, path dependence can facilitate technological development when solutions that are historically built in industrial structures come to be confronted with new possibilities. Thus path dependence can contribute to technological development through the reuse of existing knowledge, the "black-boxing" of some problems and allowing developers to focus on other, more restricted and soluble problems.

Finally, this paper suggests a need be more sensitive to the conditions under which path dependence is likely to emerge and the methodologies we use to study path dependent sequences. Most studies of change in industrial networks suggest that both self-reinforcing and reactive sequences of events are common. Since studies of the evolution of industrial networks have largely focused on technological change the pervasiveness of path dependence is hardly surprising. It remains to be seen whether or not more other types of change (e.g. institutional) exhibit the same characteristics. In any case, the recognition of the role of path dependence requires an openness towards methodologies that treat event sequences seriously. This may require resorting to historical methods of investigation and the use of historical narratives to study the evolution of industrial networks.

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Table One

Trajectory	Period One (1960s-1974)	Period Two (1974-1980)	Period Three (1980-1985)	Period Four (1985-1987)	Period Five (1987-1989)	Period Six (1989-1992)	Period Seven (1992-1995)
Science	Ongoing research into atmospheric processes	Rowland and Molina hypothesis is published	Natural balance of depletion and renewal is thought to be maintained	Discovery of the 'ozone hole'	Discovery of the 'northern hole' and CFCs are cited as the cause of depletion	Cyclical discoveries of depletion continue to be reported	Cyclical discoveries of depletion continue to be reported
Politics		Local / regional level activity	Issue moves off the agenda	Vienna Convention is established	Agreement of the Montreal Protocol	First revision of the Protocol	Copenhagen and EC revisions of the Protocol ban CFCs by 1995. HCFC ban by 2015 put in place.
ICI	Seminar on the ecology of fluorocarbons takes place	In-house search for alternatives Intensification of industry-sponsored scientific research	In-house activity comes to a halt Some industry-sponsored studies continue	Re-opening of research into alternatives. Move to refrigeration, with associated investments Increase in funding for science at the industry level	Decision to commercially develop 134a in 4 years Industry calls for a ban	Build 3 plants and new process routes are developed for 134a. Assumptions made about HCFCs. Expansion of HFC division begins	Expansion of HFC business Massive capacity for 134a comes online by the producer industry. Prices drop below forecasts
Customer / User industries		No interest	Aerosol customers test hydrocarbons	Aerosol customers move to hydrocarbons	US auto market pushes for 134a	Substantial activity in many user sectors	Many users adopt HCFCs or switch to NIK technologies