Path interdependence and Resilience: a case study of photonics in Wales

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**Abstract**

In response to an economic shock, regional paths can adapt in a number of ways, including co-evolution of paths, or path interdependence. According to recent research by Cooke (2010; 2011), examples of this path interdependence abound in the field of eco-innovation, particularly between unlikely collaborators including automotive engineering to biofuels, or milk coolers to wind turbines. The emergence of 'unlikely collaborators', and the emphasis on connectivity and innovation, suggest that this path interdependence could be viewed using a complex adaptive systems approach. Using data collected in 2012 through semi-structured interviews with firms in the photonics cluster in the North Wales region, this paper focuses on understanding what prompts path interdependence and how this interdependence occurs. The findings point to an evolution of the firms in the photonics cluster branching into solar energy with cross-sectoral collaboration between regional solar energy firms and steel firms that produced an innovation through preadaptation. The photonics firms are altering their growth paths but the cause of this change cannot be solely linked to one specific shock. These findings have implications for both resilience theory as well as the policy debate relating to the role of regional governance in facilitating adaptation.

**Introduction**

The concept of resilience has become increasingly prominent in economic geography and regional studies as regional economies and societies struggle to respond and adapt to shocks and change. The concept is developing particular traction within evolutionary economic geography (EEG) where it resonates strongly with non-equilibrium and path-dependent notions of adaptive change (Martin, 2012). Indeed much recent work within EEG views the economic landscape as a 'complex adaptive system' (Martin and Sunley, 2006; p. 573) and asserts that major shocks exert a formative influence over how this landscape evolves and changes over time (Boschma and Martin, 2010; Simmie and Martin, 2010; Martin, 2012). This approach to economic change rejects neo-classical inspired notions of adjustment mechanisms towards any notion of equilibrium (Dawley et al, 2010). Instead in EEG, resilience is defined as the adaptive capacity of a local or regional economy or 'the ability of the region's industrial technological, labour force and institutional structures to adapt to the changing competitive, technological and market pressures and opportunities that confront its firms and workforce' (Simmie and Martin, 2010; p. 30).

Much of the emerging debate within EEG around resilience focuses upon the causal concepts of adaptation – the ability to respond to an economic shock with a movement back towards a pre-conceived development path, and adaptability – where a different kind of resilience emerges through opportunities or a decision to leave a path that may have proven successful in the past in favour of a new, related or alternative trajectory or niche (Dawley et al, 2010). This perspective suggests that the adaptive capabilities of a region's economy are likely to depend upon the nature of the region's pre-existing economy – in other words, adaptation and adaptability are likely to be path-dependent processes shaped by the region's industrial legacy and the scope for re-orientating skills, resources and technologies inherited from that legacy (Martin, 2012).

Path dependency helps us understand what shapes a region's ability to respond to a system shock but is arguably less well equipped to help us understand the process of adaptability or what might cause a region's endogenous functioning to renew or atrophy, or how regional competencies and specialisms may change and thus how 'lock-in' may be avoided (Boschma and Frenken, 2009). Indeed, path dependence at the regional level may explain stability but also system stagnation and inertia (Cooke, 2011). In seeking to understand the evolutionary trajectories of regions demonstrating capacities to transition to 'green' economic development paradigms, Cooke (2010; 2011) has drawn attention to the significant role played by instances of knowledge re-combination between firms. There is indeed a growing body of evidence indicating that fruitful eco-innovation increasingly occurs at the interfaces between firms, sectors and clusters where the cross-fertilisation of ideas may either produce new unforeseen innovations, or result in the application of old knowledge in new ways to tackle complex or wicked problems (e.g. automotive engineering to biofuels, or milk coolers to wind turbines). Such unforeseen innovations typically emerge from 'revealed related variety' or the ex post relatedness of a region's economic sectors and their trajectories (Geels, 2007; Martin and Sunley, 2008). As such, this represents a form of co-evolution of paths, or 'path interdependence' (Liu, 2009; Cooke, 2011). Understanding path interdependence thus offers the potential to understand how regional economic development trajectories change and mutate.

To date, however, there have been few empirical investigations into how these path interdependencies emerge from innovation, spin-offs and the rise of market niches at the micro or firm level. As such we have little knowledge as to how far they can effectively change the course of an industrial or development path and subsequently effect co-adaptation between firms, markets, technology, industry and institution (Liu, 2009). This paper will highlight the initial empirical findings from an ongoing project on regional economic resilience. The empirical findings are based on research in the North Wales region as it is the location of several knowledge-economy based clusters including a photonics cluster and a historically prominent aerospace cluster. To keep the focus as outlined above i.e. to understand how these path interdependencies emerge and how far they can change a development path, interview findings at the firm level from the North Wales case will be assessed in this paper.

The paper will continue as follows. The next section will introduce the core elements of complex adaptive systems analysis and reviews its application and development to date in the EEG and regional innovation literature. The following section will provide a review of the innovation biography methodology used in the fieldwork. After the methodological discussion, the review of the findings will be presented, starting with an overview of the historic economic growth paths in the region. The findings were collected using the innovation biography methodology and focus on an innovative photovoltaic (PV) steel coating technology being developed in the North Wales region[1]. The final section will be the conclusion where the issues arising from these findings will be presented and future research will be outlined.

## Review of the Literature

### *Complex Adaptive Systems Analysis*

Complexity theory considers that the world is composed of systems that are constantly adapting. Complex adaptive systems are dynamic systems able to adapt and change within, or as part of, a changing environment. There is no dichotomy between a system and its environment in the sense that the system always adapts to a changing environment. Rather the system is closely linked with all other related systems making up an ecosystem. Within such a context, change is viewed in terms of co-evolution with all other related systems, rather than as adaptation to a separate and distinct environment (Cooke and Eriksson, 2011).

In recent years, significant progress has been made in the EEG literature in applying complex adaptive systems thinking to regional economies and particularly regional innovation

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[1] Pseudonyms for both the technology and the names of the firms have been used at the request of the participants.

systems, notably with an evolutionary biology inflection rather than a physic-chemical systems model (Cooke, 2012). This has established that as complex adaptive systems, regional innovation systems are characterised by four key features. First, they are characterised by non-linear and non-equilibrium dynamics because of complex feedbacks and self-reinforcing interactions amongst components. The environment is constantly changing and as such the recursive nature of the algorithmic or evolutionary processes of variation, selection and replication never stops.

Second, they exhibit emergence in that they exhibit macro-level structures or patterns, characteristics of the system as a whole, that arise endogenously and spontaneously out of the micro-level interactions of agents and their environment. In effect, the whole is greater than the sum of its parts and applies to many every day experiences (Martin and Sunley, forthcoming). As Beinhocker (2007; p. 167) observes, for example, 'what we call a symphony is a pattern of sound that emerges out of the playing of individual instruments'. In regional terms, it can be interpreted as the tendency for macro-scale structures and dynamics (such as cities, industrial districts and clusters) to emerge spontaneously out of micro-scale behaviours of agents (such as firms, workers, consumers) (Martin and Sunley, forthcoming).

Thirdly, complex adaptive regional innovation systems are imbued with self-organising and co-evolutionary interactions among their constituent components and elements. They exhibit an adaptive capacity which enables them to re-arrange their internal structure and dynamics spontaneously, whether in response to changes in the external environment (e.g. external shocks), or from within through co-evolutionary mechanisms or in response to 'self-organised criticality' (Martin and Sunley, 2007). As such they are autocatalytic (they drive their own growth) but in ways that cannot be foreseen. Each member of the population or entity in the system is continually searching for new ways of adapting to the environment. Thus knowledge about the environment and how it is changing is the key to self-organisation and the ability of entities to understand how and in what ways they need to adapt in order to survive (Cooke, 2012).  In short, economic self-organisation brings immense complexity through acquired energy and acquired knowledge which in combination yield creativity in economic evolution (Foster, 1997). Creativity and innovation thus play an integral role in system dynamics and indeed, may be regarded as the 'evolutionary fuel' of complex systems (Cooke, 2012).

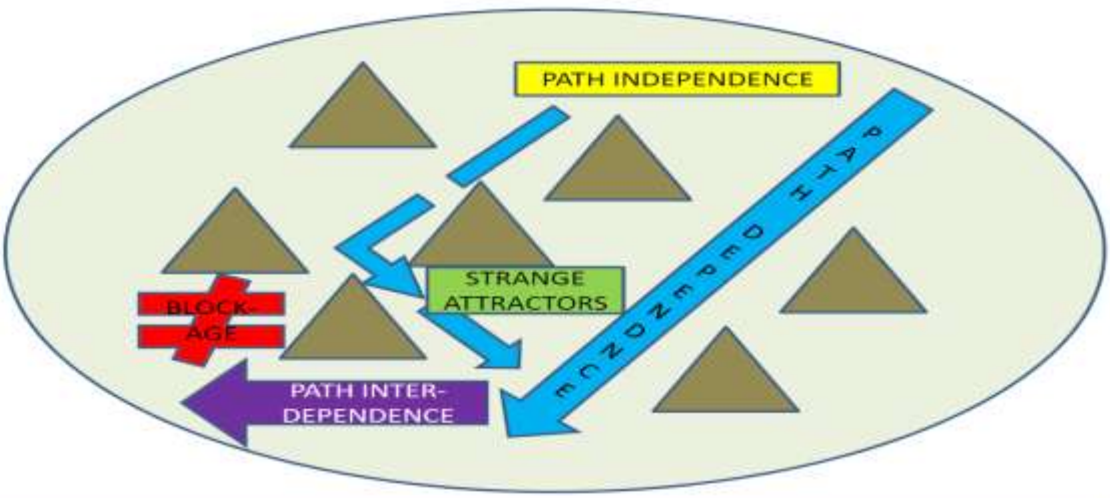
This leads into to the fourth key characteristic of complex adaptive systems which is that they are not uniform and homogenous. Rather, they are characterised by an ontogenetic topology. This reflects the understanding that complex systems have a particular 'fitness landscape' that in visual terms represents a mountainous (or ontogenetic) terrain between peaks of high fitness (where entities are well-designed to fit the needs of their environment and from which all paths are downhill to lower fitness), and low fitness valleys (from which most paths lead uphill). These fitness landscapes may take various forms. They may be a rugged topography of hills and valleys, or sleek, or have variations in between. The sleeker the landscape, the more stable the system because there are fewer sources of perturbance and little opportunity for communication between system entities. The more rugged the landscape, the more conduits and tributaries that exist that act as communication lines between centres of energy or potentially interacting entities, and so the more unstable the system. When such interactions are abundant, the system is said to be operating at the 'edge of chaos' or to be highly susceptible to system change or shocks (Kauffman, 1995; 2008). The greater the interactions between entities, the greater the likelihood of emergent properties and phenomena (Cooke, 2012). In essence, 'too much structure creates gridlock…too little structure creates chaos' (Brown & Eisenhardt, 1998; p. 14, cited in Baum & Silverman, 2001). If the system can remain in this chaotic mode, sustainable adaptive functioning can be achieved which supports learning, flexibility and adaptation amongst the system's entities.

*Path dependence and interdependence*

Complexity theory thus highlights 'the tension between exploitation of knowledge gained (path dependence) and exploration of novel actions (path creation) and illustrates how innovation processes characterised by 'edge of chaos' behaviour balance these tensions, permitting adaptive functioning of technological-organisation systems' (Baum and Silverman, 2001; p. 198). As such, complex adaptive system thinking also provides interesting insights into the nature and form of interactions that can occur and their resulting innovations. The system's fitness landscape has certain constrained pathways which are known as 'attractors'. These are the routine or 'normal' self-organised behaviours or interactions in the system between entities and with the system and its environment (such as cyclical or neighbourhood effects). These create normal path interactions that in economic systems we understand as path dependence and which emerge from routine related variety (Cooke, 2012). One variant of these interactions are 'strange attractors' where there is no a priori reason why such paths might coalesce and where unexpected combinations of pathways occur to produce innovative new pathways. As such strange attractors display 'revealed relatedness' rather than obvious relatedness. Furthermore, the more unlike or strange they are, the more radical the innovation conceived by the interdependent paths will be (Kauffman, 2008; Cooke, 2011).

Cooke and Eriksson (2011) depict the outcome of strange attractors visually (Figure 1). This demonstrates a rugged system landscape where there are multiple fitness peaks or mountains (depicted by the triangles), and a range of paths between them. The higher the connectivity the more rugged the system becomes i.e. a system that has low connectivity will only have one peak. However, a system with high connectivity will have many peaks which is the case here. The paths are moving down the peaks to the valleys which are areas of increased interaction. The catalyst for the intersection of these paths is the 'blockage'. The blockage can represent different events such as an external shock to the system. At the point where the path runs into the blockage it can do four things: (1) end, (2) redirect temporarily and return to its path over time, (3) go in another direction, or (4) intersect with another path in the valley. The fourth scenario, where at least two paths intersect, results in path interdependence. However, not all paths are destined to intersect.

Figure 1:




Complex Adaptive System Topology for Innovation

Source: Cooke & Eriksson, 2011

*Preadaptation and the adjacent possible*

There are two main types of innovation that can result from the meeting of strange attractors: preadaptation and the adjacent possible. Preadaptation is rooted in evolutionary biology and is a type of technology transfer where an innovation from one industry setting is adapted for wholly different industry solutions in another. The adjacent possible is an incremental innovation that is closely related to an existing product and where a design effort must be effected to execute an innovative improvement (Cooke, 2011). This simple innovation becomes radical when it is recombined with existing resources (Kauffman, 2008). Complex adaptive systems thinking suggests that both types of innovation are more conducive to a region with related variety and connectedness as there is more potential technology transfer and recombination than in a specialised region. Kauffman (2008; p. 151) asserts 'the more diverse the economic web, the easier is the creation of still further novelty'.

Using this approach, and the empirical findings from the photonics firms in the North Wales case study, there are two main research questions that will be discussed in this paper. Firstly, how do different paths combine and co-evolve; and secondly, what types of innovation result from this path change?

**Methodology**

For this research, we have used an innovation biography methodology. This is a methodology that is qualitative in nature, primarily utilising secondary source analysis and semi-structured interviews at the firm's location to get an understanding of the organisational structure of the firm itself as well as the innovation that the firm produces (Bruns et al, 2011). The starting point of the innovation biography is choosing the actual innovation. Once the innovation is chosen, the subsequent biography traces the innovation backwards and, through secondary source analysis and interviews, provides an in-depth understanding of how the innovation was created. The secondary source analysis not only informs the interviewer about which firms are key actors in the innovation development, but also informs the interviewer about any policies or other social factors that may have influenced the innovation. The firms that have been interviewed are chosen largely based on the results of the secondary source analysis, and have a relationship to the innovation that is the focal point of the methodology. This methodology is widely used in industries such as biotechnology and pharmaceuticals where the innovation's history may be far-reaching and relatively intricate (Bruns et al, 2011). Thus far, nine semi-structured interviews with academics, industry and knowledge network actors based in North Wales have been completed.

**Path Interdependence in Case Study Region**

The photonics cluster and the aerospace cluster, co-located in North Wales, have evolved independently over decades. The aerospace cluster started in the 1930's due to the British War Ministry's shadow games. They sought a defence research and manufacturing site that was in a rural setting proximate to major cities which the North Wales region could provide (Clifton et al, 20011). The aerospace SMEs and larger firms that have emerged over time to compose the regional cluster are mainly based there as part of the supply chain for the anchor firm, Airbus (Clifton et al, 2011). As the regional steel industry pre-dates the aerospace cluster, it could be argued that access to high-quality steel products was another reason for the cluster to originally locate in North Wales region.

Coinciding with the evolution of the aerospace cluster, the regional photonics cluster has evolved since the 1950's (Goodwill & Gauge, 2010). The original anchor firm in the cluster was Pilkington Optronics (PO), a subsidiary of the Pilkington Glass firm also located in the region. PO's original aim was photonics; however, through partnering with US firms, focused on photonics for military technology, the defence emphasis was introduced making PO a photonics firm specialised in defence manufacturing. This defence specialisation should not be confused with the initial defence specialisation of the regional aerospace cluster as these two events are unrelated (Goodwill & Gauge, 2010). Nonetheless, the photonics for defence aim still stands at the current time (2013). Other SMEs have emerged in the region due to the high-skilled human capital, government funding and technological relatedness of their products to photonics. These firms are not a part of the supply chain for the photonics cluster; rather, they innovate with photonics technology in other fields including solar energy.

This brief regional account of the economic growth paths is interesting as it highlights the evolution of the two most prominent knowledge-economy based clusters in the region and places the regional steel industry as part of the supply chain for the aerospace cluster. However, from 1988, with the privatisation of the steel industry in Britain, the once declining steel industry has rebounded to be a contributor to regional economic growth. After having several different owners, Company B (buying out Company C in 2007) is now the major steel firm in North Wales that is innovative and focused on developing technologies that reduce the effects of climate change. Through this new focus on innovation, in a traditionally non-knowledge economy based industry, we now have the basis for potential collaboration leading to path interdependence between steel and solar energy firms in North Wales.

**Strange Attractors: Solar Energy & Steel**

From this brief review, the solar energy firms that have emerged in the region are a result of further diversification of the regional photonics cluster. The defence emphasis still remains in the majority of the regional photonics cluster firms which indicates that the photonics path is branching into solar energy as opposed to path breakage. Interestingly, a connection between these unlikely collaborators has occurred with the knowledge-based solar energy firm, Company A, and the steel industry anchor firm, Company B, producing an innovative PV steel coating technology.

*Recombinant Innovation: PV Steel Coating Technology*

The PV technology that is used in this innovation is an adaptation of the technology originally developed by Michael Graetzel and Brian O-Regan at the E'cole Polytechnique Federale de Lauanne in 1991 and was originally referred to as the Graetzel cell. The PV technology is described as artificial photosynthesis (Company A Interview, 2012). The three main components of the technology are: an electrolyte, a layer of titania (a pigment used in white paints and tooth paste) and ruthenium dye sandwiched between glass. When sunlight strikes the dye it excites electrons which are absorbed by the titania to become an electric current than can be converted into electricity for domestic use. Unlike previous versions of this technology, the components of the Company A technology are non-hazardous and do not have varied reactions to temperature changes in their ambient environment. In regards to commercialisation potential, the technology does not need direct sunlight to function, making it ideal for Northern European countries. Furthermore, the connection between photonics and this technology is clear.

> *The basic technology behind that [Company A technology] is pure photonics. You're taking photons from the sunlight, passing them through materials which exhibit electronic changes, emits electrons which then are converted into, well create current and are converted into A/C current for our applications. So Company A is an absolutely pure photonics company because they are working with the basic materials and one of the reasons that they came to Wales, to north Wales, was that they were looking for research facilities, and that's how they set up. (Welsh Optronics Forum Interview, 2012)*

The technology has been established since the 1990s; however, Company A's innovativeness is in its application of it. Through their collaboration with Company B, Company A, is actively researching a way of adding the PV technology to steel through a coating process. In June 2011, as a result of this collaboration, the development of the world´s largest dye sensitized photovoltaic module, printed onto steel in a continuous line was created (Company B Interview, 2012). Later, in November 2011, Company A and Company B announced the targeted development of Grid Parity Competitive Building Integrated Photo Voltaics (BIPV) solar steel that does not require government subsidised feed in tariffs. This 'solar steel roofing' is installed on the Sustainable Building Envelope Centre (SBEC) 'living lab' facility in North Wales.

*Overview of Firms: Company A*

Company A, founded in 2004, is a global supplier of innovative PV technology. The firm was originally based in Australia but has reached the status of a multi-national company with its first UK site in North Wales, despite having a fairly small workforce of 70 people. Company A chose to base their UK operations in NW due to the funding available in the EU Convergence region and because of the emerging regional emphasis on solar energy provided through the diversification of the photonics cluster. The firm is part owned by German retail ownership, it has Australian ownership, and it is 20/25% owned by insiders. The phenomenal growth of the firm is largely attributed to their innovative applications of the PV technology. To this extent, Company A partners with leading MNCs who are well-regarded in their specific field, ex. Company B, to establish new routes-to-market through adding their PV technology to the existing products.

> *… we [Company A] are looking to make buildings as power stations, they have lots of buildings, large roofing areas in Tesco's or B&Qs and we would like to have all that roofing area covered with PV [photovoltaics]. Essentially each building would be a power station in its own… there's so much redundant space which can be converted and with the price of oil, which is only going to increase, PV is probably one of the leading alternatives. (Company A Interview, 2012)*

In attempting to convert buildings to be energy producers instead of energy consumers, Company A has collaborated with both Company B as well as with Pilkington Glass in the US (no affiliation with the Pilkington firm formerly located in North Wales). The North Wales collaboration pre-dates the collaboration in the US but the US collaboration has produced faster results through BIPV ie. glass on buildings can produce energy through the PV technology as a coating that is added to it.

In regards to the collaboration in North Wales, the feasibility study started in 2006 between Company B's predecessor, Company C, and Company A.

> *..[Company C was chosen] at the time, had their colour coating facility here, they do a lot of colour coating work here and that had a lot of synergy with what we wanted to do, we especially wanted to take a steel strip and coat it with our PV technology or functional layers so there was a lot of synergy with what they were doing. They tend to put on insulating layers in paints, etc. (Company A Interview, 2012)*

At this point there were less than 10 employees working on the project. From 2007-2008, the project was sponsored by the Department of Trade & Innovation at the UK government level.

*Overview of Firms: Company B*

Company B, previously Company C, has been a regional presence since the 1960s. While owned by Company C, the NW plant manufactured steel but was also researching innovations in steel with the main output being 'Colour Coatings' which served a two-fold purpose. First, they allowed steel to be mass produced in varying colours to meet the specifications of the clients. Second, the colour coatings allowed a more energy efficient building as they eliminated any gaps where cold air could seep into the building. With the takeover by Company B, little changed with the general output of the facility, steel was still produced and coatings were still made; however, Company B researchers became interested in using the coatings in new ways and what that could do for the building.

In 2007 Company B executives, as well as representatives of the supply chain, discussed the long-term strategy of the firm in the region and how they would innovate into the future, particularly given the growing issue of climate change. When considering the future innovation strategy the executives decided to focus on sustainability and received over 200 ideas for future growth. Of those 200 ideas, 5 were taken further through collaboration. All 5 of these projects focused on using the existing Company B technology that was developed in the region in new and innovative ways, that were sustainable in nature, particularly relating to the capture, storage and delivery of energy. Through focusing on these themes, the firm wanted to shift from creating buildings that use energy, as buildings account for approximately 40% of all $CO_2$ emissions, to creating buildings that produce energy (Company B Interview, 2012).

This was Company B's first attempt at open innovation and it proved successful through producing several technologies. The most technologically challenging and complex of the five main projects is the on-going collaboration with Company A which would enable the PV technology to be added as another layer to the existing coatings on steel that is being manufactured at Company B ie. another coating to be added to the colour coatings Company B was accustomed to designing.

*How did the Path Interdependence Emerge?*

The path interdependence described in these findings initially emerged through economic and market changes for both Company A and Company B. For Company B, the path adaptation was in response to the shock of climate change and what that continues to mean for the steel industry as a whole. In order to remain competitive and innovative, Company B collaborated with Company A to produce a recombinant technology that was formed through preadaptation. For Company A, the collaboration was part of their ongoing business strategy and cannot be directly attributed to a specific shock. However, it could be argued that the recent economic crisis has accelerated this collaboration to the current stage with an advanced product.

Company A acknowledges that they have felt the impact of the recession and, as a result, have increased their collaborative efforts due to shrinking funding opportunities. An output of these collaborative endeavours is the Solar Photovoltaic Academic Research Consortium (SPARC) project. The project is a collaboration between regional industry, University and government with the goal of advancing solar energy, through thin film PV technology and smart meter systems. In addition to this on-going project, Company A also applies for Technology Strategy Board (TSB) funding, and Framework Programme 7 funding. This ability to apply for particular funding streams that may only be available to firms in convergence regions reinforces the firms' original reason to locate in the NW region.

> *It [the recession] pushed us towards collaborations. Before that it was, 'well we've got enough money and we don't need to worry about it', our share price was booming at the time. But there has been a general recession in the solar market and if you think of it, some very large companies have gone bust –much larger than Company A. (Company A Interview, 2012)*

Beyond these collaborative products, Company A is also planning to continue using their PV technology in new and innovative ways on a smaller scale. Thus far, the collaborators Company A has chosen to work with have been in the industrial sector; however, Company A has noticed a niche in the market for their product that, although using much less of their technology, could have a much bigger impact: cell phone battery charging. The firm would like to work with cell phone manufacturers in the future to recombine their technology in an effort to have a self-charging cell phone.

**Conclusion**

This paper presents findings from the NW case study where firms that would seemingly be unlikely collaborators are developing what could be a radical innovation. The 'unlikely collaborators' are Company A, a solar energy firm, part of an MNC, that recently located to the North Wales region due to the convergence funding available to them and Company B, a large steel production firm, part of an MNC, that has historically been located in the region but has only recently focused on climate change-related innovation. The 'radical innovation' would actually be both a product and a process. The product would be steel (from Company B) that is coated with PV technology (from Company A) using a coating process originally patented by Company C that has been updated to include the PV technology coatings ie. recombinant innovation through preadaptation. Although this technology has yet to be commercialised, it would be a major breakthrough independently, or in addition to the glass BIPV, at the global level having buildings as energy producers instead of energy consumers. This finding, with two unlike collaborators merging to create a radical, recombinant innovation, supports the strange attractors concept (Kauffman, 2008; Cooke, 2011). It should be highlighted that the catalyst, or blockage, for these strange attractors to meet was a shock, but it was not the macro-economic shock of the recession. Rather, Company B places significant emphasis on climate change as a reason to focus on collaborations of this kind as government policy to reduce carbon emissions directly affect their industry with buildings traditionally acting as energy consumers instead of energy producers. Alternatively, Company A was interested in this collaboration for more economic reasons as they wanted to have both a UK site and a UK- based, steel producing partner to fit into their overall business strategy. When the technology is commercialised, it will be interesting to see how this path co-evolution impacts the other solar energy and photonics firms in the region.

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