**Institution: University of Surrey**

**Unit of Assessment: UOA 10 Mathematical Sciences**

**Title of case study: Modelling the evolution of a bio-based economy in the Humber region**

## 1. Summary of the impact

Industrial regions around the UK are seeking to develop bio-based economies in order to minimise their CO2 emissions and stimulate economic regeneration.

Researchers at Surrey, in collaboration with key industrialists from the Humber region, have produced a mathematical model of the main factors influencing the transition to, and establishment of, a bio-based economy. This model has been used by the Humber Environmental Managers (HEM) group, and the Humber local authorities to help guide strategic planning for the region. The outcome is that the research has contributed to environmental improvement and economic regeneration of the Humber region, and has indirectly impacted on public policy.

## 2. Underpinning research

The Surrey team, led by a mathematician (and consisting of environmental scientists, sociologists, engineers and computer scientists) was formed in 2010, as part of the EPSRC-funded "Evolution and Resilience of Industrial Ecosystems" (ERIE) project, to study the application of complexity science to social and economic systems.

The Centre for Environmental Strategy (CES) has run a longstanding case study of the Humber region, which is one of the UK's major energy generators and CO2 emitters, and they introduced ERIE to Humber. To initiate the project, researchers carried out 18 interviews with key stakeholders in the region to survey the main issues, identify parameters, and specifics that needed to be addressed for the Humber region. The development and analysis of these interviews were underpinned by quantitative sociology and complexity science. An important problem which emerged was how to mathematically model the transition from a predominantly fossil fuel based economy to a bio-based economy. A mathematics-sociology team then set in motion a strategy for modelling the transition.

The Surrey team led by David Lloyd (Lecturer in Mathematics) and Alexandra Penn (ERIE Research Fellow) consists of Lauren Basson (Lecturer in CES), Angela Druckman (Senior Lecturer in CES), Frank Schiller (ERIE Research Fellow), Chris Knight (ERIE Research Fellow), Amy Woodward (ERIE PhD student, and ERIE Administrator) and Daniele Avitabile (former ERIE Research Fellow, now Lecturer at Nottingham). Kasper Kok (Lecturer, University of Wageningen, Netherlands) facilitated the participatory modelling exercise.

On the basis of the requirements identified via the aforementioned interviews, the ERIE team studied the "participatory modelling" literature to identify an appropriate modelling strategy capable of representing the interaction of the key factors influencing the Humber region. The basic model proposed was a Fuzzy Cognitive Mapping (FCM), which was formulated as a dynamical system, $X(n+1) = f(AX(n))$, where $X$ has $m$ components, A is a weighted connectivity matrix, and $f$ is a mapping. The connectivity matrix A was formulated via "participatory modelling": the participants identify key factors that will influence the development of a nascent bio-based economy (land availability, fossil fuel price, community acceptance, etc), and they are weighted and linked by a directed graph. Participatory modelling was used as it has the significant advantage of establishing the engagement and buy-in with stakeholders that are vital for any model to have impact in decision-making. FCM in particular was used as it is a well-established modelling methodology for exploring complex issues with stakeholders that is able to yield quick and useful results during a workshop, and is amenable to a dynamical systems analysis.

The HEM group welcomed the initiative and the first meeting was held in November 2011 in

Humber with 12 local industrialists and policy makers, including members of the regional HEM group and the South Humber Gateway Board (SHGB), with the Surrey team leading the meeting. The meeting participants were guided to create links between these factors and describe the links' strengths. These factors were then connected with a cognitive map. The connections were each assigned a weight, and they formed the entries of the connectivity matrix. By then choosing an appropriate *f* the dynamical system could be implemented immediately at the meeting and a range of scenarios tested. The results of this meeting led to the paper of Penn et al. (2013).

Once the main parameters of the model were proposed it was important for the mathematicians to test for robustness of the model. Dynamical systems theory, with appropriate modification for the constraints induced by the connectivity matrix, was applied to the model. Different representations for *f* were tested, the fixed points of the model were identified, and stability and dynamics tested. The principal nonlinear *f* tested was the *sigmoidal* model. These results were reported in Knight et al (2013). This research was then fed back into the next iteration of the model development.

Since the initial workshop, the Surrey team has met regularly with the HEM and SHBG groups and members of the Local Authorities, with two subsequent workshops in February 2012 and 2013, firstly with HEM and then with the larger group, with the February 2012 meeting used for verification of the FCM. The model continues to evolve taking into account feedback from the HEM group. Current improvements include coupling to take into account feedback control and exploration of regionally contentious feedstock supply and land use scenarios.

**3. References to the research**

The development of the model has been on going and as new versions emerge they have been presented to the HEM group. Feedback from these presentations has then been used to further refine the model. A paper based on this sequence of interactions has appeared in PLoS ONE (Penn et al, 2013). Since the analysis is based on participatory modelling, it is natural for the paper to appear coincident with the impact. A second paper (Knight et al, 2013) gives a dynamical systems analysis of the model.

- A.S. Penn, C.J.K. Knight, D.J.B. Lloyd, D. Avitabile, K. Kok, F. Schiller, A Woodward, A. Druckman, and L. Basson (2013) *Participatory development and analysis of a fuzzy cognitive map of the establishment of a bio-based economy in the Humber region*, PLOS ONE, DOI: 10.1371/journal.pone.0078319.
- C.J.K. Knight, D.J.B. Lloyd, and A.S. Penn (2013) *Linear and sigmoidal fuzzy cognitive maps: an analysis of fixed points*, Applied Soft Computing (accepted, in press).

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The HEM is made up of representatives of local heavy industries, conservation organisations (NGOs) and other key regional figures, for example the National Industrial Symbiosis Programme. It is a collaborative group which discusses issues relevant to industry and sustainability in the region. It allows industry, conservation bodies and local authorities to communicate and come up with strategies and solutions for common problems.

The SHGB is a strategic regional planning group whose members include North Lincolnshire Council chief executives. The board's terms of reference, include "providing strategic direction" to the South Humber Gateway and "identifying constraints to investment and development and seeking their early resolution."

http://www.northlincs.gov.uk/business/investing-in-north-lincolnshire/southhumbergateway/shgb/

## 4. Details of the impact

Development of models that engage and help policy makers make informed decisions remains a significant problem for complexity science research. The current case study based on the Humber region is a step in this direction. Managing the development of a new bio-based economy in the Humber region requires the understanding and modelling of complex, interacting, socio-economic factors.

The impact of the research is twofold. Firstly, the participants and policy makers were introduced to systems level and complexity-science based thinking about the key factors influencing the start-up of a bio-based economy, how these factors interact with each other, and how to turn the information into a mathematical model. The response of the HEM group and other stakeholders to this approach has been enthusiastic with over half the participants of the original workshop sending long responses suggesting improvements to the model highlighting their important engagement in the process. For example, the CEO of Global Biotechnology Transfer Foundation, a not-for-profit United Nations partner organisation, wrote "*I found the interaction with the FCM workshop both useful and enlightening and in particular the mathematical modelling aspect. The FCM exercise significantly affected my thinking ….*"

The Programme Manager for Humber Chemical Focus Ltd) wrote: "*The FCM workshop was useful and informative. This interaction between multiple organisations on the same topic is useful and cannot easily be replicated in normal business-public sector interactions. The FCM modelling approach had a clear impact on this interaction*."

While the model is becoming progressively more complex, it is also becoming easier for the managers to use. The model explores the consequences of several scenarios that might influence the start-up of a new business sector. This output has flagged up key points for the HEM group and the South Humber gateway delivery board when discussing strategy related to a bio-based economy. Since several industries, NGOs and local authorities have taken part in the modelling process and are carrying out R&D in various bio-based technologies or are involved in regional planning, the model automatically has engagement with the decision makers -- in particular the SHGB and Local Authorities who carry out strategic planning for the region. They do not make policy, but make highly influential decisions about the region's future, and therefore indirectly impact public policy.

Secondly, a tool for investigating various policy/strategy decisions based on network-flows was created. The main aim of the model is to generate a set of questions for decision makers to think about when designing policies or making strategic decisions. The ERIE project now has an established engagement with HEM and SHGB with additional evolution expected to develop over the next three years.

At present the principal target audience is the team in the Humber region. As the methodology develops and becomes more generic, it is planned to roll it out to other regions. Preliminary discussions with DEFRA (Department for Environment, Food and Rural Affairs) have taken place.

## 5. Sources to corroborate the impact

The principal impact is on the strategy and implementation policy of the range of government groups (HEM, SHGB), heavy industry, and NGOs. The principal impact on the HEM and SHGB will be an impact on the environment and indirectly on the economy, since one of the primary focuses is the transition to a green economy.

The impact of the FCM exercise has been documented in statements from

1. The Programme Manager at Humber Chemical Focus Ltd (www.hcfhumber.co.uk)
2. The Chief Executive Officer at Global Biotechnology Transfer Foundation, an international

not-for-profit United Nations Foundation partner organisation. Their mission is to promote awareness of the potential for biotechnology to support sustainable, long-term, socio-economic development. (NB. The CEO has since joined the ERIE Advisory Board, as a result of his interest after participating in the FCM Workshop.)

Additional impact is corroborated by :

1. The Environmental Manager at Croda Europe Ltd. Contact details provided.
2. A representative of the Economic Regeneration Department of the North East Lincolnshire Council. Contact details provided.
3. The Company Director of Link2Energy. Contact details provided.

The above letters and emails establish (1) the importance of looking at the bio-based economy for the Humber region and further afield, (2) That they found the interaction with the FCM workshop/ERIE useful and enlightening. (3) That the interaction has helped change their thinking or any decision pathways.