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Comparing a simulation model with various analytic models of the international diffusion of consumer technology

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ABSTRACT

In this paper we propose and evaluate a method for studying technology adoption at the national level using hybrid simulation. A hybrid simulation model is developed which combines elements of system dynamics and agent-based modelling, and treats nations as adopting agents. International diffusion is modelled as a social system where the adoption of an innovation, or even just growing pressure to adopt an innovation, in one nation can then influence its adoption in others. The model is used to investigate nine different technological innovations for which sufficient international data are available. Using the available empirical data, the method of differential evolution is used to configure the model which allows the parameter space to be explored in an efficient manner, without bias or subjective disagreement. Good agreement is found between the parameters derived in this way and those reported to configure analytic models. For each of the nine innovations, we report the rank order correlation between the actual order of adoption of the innovations by nations and the order predicted by the simulation model. We also report the rank order correlations between the actual order and the order predicted by a much simpler statistical model. Improvements in the rank order correlation are shown when some form of social influence between nations is included, although there is no significant difference in results between the four different types of social influence considered by the simulation. The nine technologies investigated also appear to fall into two groups with significantly different uptake speeds. Advantages and limitations of the approach are discussed along with suggested implications for practice.

1. Introduction

Research into the diffusion of innovations primarily considers the influence of communication channels over time within a social system comprising defined members (Rogers, 2003) who are typically identified as individuals or organisations. However, despite a considerable body of technology diffusion research, relatively little attention has been paid to the case of nation states as the adopting agents. This is perhaps surprising considering the importance of such adoptions which might relate to technological infrastructure, national standards, protocols, etc. Furthermore, many such adoptions at the national level can be significant drivers of social change. In this paper, we focus on modelling the national adoption of various technological innovations. Dekimpe et al. (2000) appear to be the first to explicitly consider the nation state as the adopting agent in their examination of the breadth and depth of cellular technology adoption. Some earlier work had considered it less directly, e.g. Antonelli (1986). While considering the diffusion of modems, he treats nations as adopting agents in one part of his analysis where he examines the diffusion lags of 16 nations. Even fewer publications consider diffusion processes in the context of an international social system of nations, tending to focus instead on in-nation diffusion or the comparison of in-nation diffusion across nations from which general conclusions are drawn and often described in the context of international diffusion.

Analytic models, and especially epidemic models (Geroski, 2000), are used extensively to capture longitudinal and spatial trends, but these models tend to be constrained regarding the extent to which the social system of nations is represented. In this paper a simulation model, as opposed to an analytic model, that combines the system dynamics and agent-based modelling paradigms is introduced. The innovation in this mixed approach is that it allows examination of international diffusion as a 'social' system (where the adoption of a technology in one country can influence its adoption in another) and explores both the temporal and spatial dynamics of this process. As such, this work provides a novel contribution to the research domain of innovation diffusion.

1.1. Simulation as opposed to analytic modelling

The paradigms of system dynamics (SD) and agent-based (AB) simulation are both well established with much published literature,

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spanning decades of research. Both have been widely applied across many domains to predict system behaviour using either deductive SD or inductive AB approaches (also commonly referred to as top-down and bottom-up approaches, respectively). As such, these paradigms represent complementary approaches to modelling and simulation. Furthermore, each paradigm has its own particular characteristics that make it suitable for modelling certain aspects of systems (Swinerd and McNaught, 2012).

Representing resources and dynamics within a system as a set of stocks and flows, SD captures feedback and delay processes to model system behaviour over time. The stocks provide aggregate representations of entities within a system, with flows that are regulated by feedback. Due to the inherent delays, the resultant system behaviour can be non-linear and counter-intuitive. Resource flows correspond to the mean rates at which entities within the system change state. Sterman (2000) provides an example of an SD model relevant to the aggregate diffusion process implemented using a modified form of the Bass diffusion model (Bass, 1969).

AB modelling represents system entities as individuals. Referred to as agents, these entities interact with each other and their environment according to rules which are often simple and local in nature and from which higher level system behaviour can be generated. Facilitated by the advent of object-orientated programming and implemented using asynchronous programming techniques, agent interactions are usually defined by a set of decision-making rules with the agents given sufficient autonomy to interact with each other and the environment such that temporal and spatial macrobehaviours (aggregated behaviour at a level higher than that of the rules allocated to agents) can be generated and observed. Rixen and Weigand (2014) provide an example of AB simulation modelling for the diffusion of smart meters.

Simulation provides a tool for formally testing a dynamic hypothesis and determining its adequacy (Homer and Oliva, 2001). In contrast to a simulation approach, most studies of the international diffusion of innovation use analytic models. These mathematical models tend to use a regression model in which proxy measures are often used as the covariates of operational parameters in order to represent behaviour or attitudes (national characteristics). Analytic models are useful for capturing the structure of diffusion processes, but, unlike simulation modelling, cannot capture adaptive behaviour so easily.

In reviewing innovativeness and adopter categories, Rogers (2003) identifies 26 generalisations covering social, economic and environmental factors which affect individuals or organisations within the social system. These factors help determine the responses of members of the social system to innovation, especially regarding its timing and their willingness to adopt, categorising members of a social system as innovators, imitators or laggards. Analytic models tend to use proxy measures to represent such generalisations and, therefore, to represent and identify national characteristics that are key to diffusion processes.

While the observations of Simon (1996, p. 62) appear to support the use of aggregate measures within models to represent key national characteristics, we consider whether a social system comprising a set of nations can be represented in a richer way, using a hybrid simulation approach, than is possible with analytic models.

2. Literature review

A review of studies explicitly reporting models for the international diffusion of technology is summarised in Tables 1 and 2. As can be seen, there is a range of proxy measures used to describe the characteristics of nations, drawing mainly from physical and human geography; the choice of proxies is often accompanied by arguments as to their suitability.

Based on the references included here and the wider literature, we identify five internal characteristics and use these in the tables to categorise the use of proxy measures. This is not intended as an authoritative categorisation, but is a compromise representing the diversity of measures used across studies and the arguments made for their inclusion. Islam and Meade (2012) also use five characteristics: economic activity; access to information; culture and innovation; economic and ethnic heterogeneity; and demographics. The five characteristics used here are similar but allow for the inclusion of national dogma, represented here as the characteristic of authority and law. The tables also represent the scope of cited studies, describing the number of nations included, *m*, along with the technologies and timeframes considered.

Recognising that reasoned action is a mix of intrinsic intent and external influence (Fishbein and Ajzen, 1975), the difference between those studies represented in Table 1 and those represented in Table 2 is the manner in which external influence upon nations is represented. Those in Table 2 incorporate specific measures of social interaction whereas those in Table 1 do not.

In order to highlight this difference, the work of Gatignon et al. (1989) (GER) is introduced as an example from Table 1 with the proposed extension to this model by Kumar et al. (1998) (KGE) as an example from Table 2.

In discrete form, GER define their diffusion model as:

$$S(i,t) - S(i,t-1) = [p(i) + q(i) \times S(i,t-1)] \times [1 - S(i,t-1)] + u(i,t) \qquad (1)$$

where S(i,t) is the cumulative penetration of an innovation in a nation i at time t, the propensity of a nation to innovate is given by p(i) and to imitate by q(i) (sometimes referred to as internal and external influence, respectively) and u(i,t) is a disturbance term. It is through these coefficients that the characteristics of nations are captured using weighted proxies, Z(i), of national characteristics:

$$p(i) = Z'(i) \times g_p(i) + e_p(i) \;; \qquad (2)$$

and

$$q(i) = Z'(i) \times g_q(i) + e_q(i) \qquad (3)$$

where g(i) is a weight and e(i) is a disturbance term. This form of regression model can be used to analyse important characteristics associated with innovation diffusion within a nation. A comparison across nations is used to make generic observations or to differentiate national behaviour. However, this model does not explicitly capture interactions between nations and is, therefore, represented in Table 1.

KGE propose an extension to this model including a time lag relative to the 'lead nation', i.e. the first nation to adopt the innovation (Beise, 2004).

$$q(i) = Z'(i) \times g_q(i) + \tau(i) + e_q(i) \qquad (4)$$

where $\tau(i)$ is the time lag of nation i relative to the time at which the lead nation adopted. The additional term is applied only to the coefficient of imitation as time lag is not applicable to a nation's propensity to innovate (Bass, 1969). This modification allows the impact of lag between a nation and the lead nation to be explicitly analysed and, therefore, is represented in Table 2.

Putsis et al. (1997) develop a diffusion model specifically to represent cross-nation mixing. This model stands out from those summarised in Table 2 because it incorporates temporal dynamics as a feature of external national influence as opposed to static measures of bilateral influence. Their model uses proxy measures to represent two parameters — TV sets per capita as a proxy for non-word-of-mouth information and GDP per capita as a proxy for information-seeking and susceptibility.

There are 8 studies summarised in Tables 1 and 9 in Table 2 that, collectively, establish the use of socioeconomic proxies to represent key characteristics of nations. The number of national characteristics included per study is typically 3 or 2, respectively, suggesting that fewer internal measures are required when external influence is explicitly modelled. The use of the defined national characteristics is fairly even with no clear distinction across the studies represented.