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A general framework for analyzing techno-behavioural dynamics on networks

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A B S T R A C T

A general framework for assessing future impacts of technology on society and environment is presented. The dynamics between human activity and technological systems impact upon many processes in society and nature. This involves non-linear dynamics requiring an understanding of how technology and human behaviour influence each other and co-evolve. Conventionally, technological and behavioural systems are analyzed as separate entities. We develop an integrated theoretical and methodological approach termed techno-behavioural dynamics focussing on networked interactions between technology and behaviour across multiple system states. We find that positive feedback between technology learning, evolving preferences and network effects can lead to tipping points in complex sociotechnical systems. We also demonstrate how mean-field and agent-based models are complimentary for capturing a hierarchy of analytical resolutions in a common problem domain. Assessing and predicting coevolutionary dynamics between technology and human behaviour can help avoid systems lock-in and inform a range of adaptive responses to environmental and societal risk.

1. Introduction

Understanding the future impacts of technology on society and environment is of fundamental importance. For instance, low carbon technologies play a central role for climate mitigation (IPCC, 2011), and the rapid adoption of information and communication technology (ICT) is altering economic and environmental systems (Hilty et al., 2006; Basole and Rouse, 2008). Emerging technologies will become increasingly ubiquitous and non-invasive across society and environment (Bohn et al., 2004). Synergistic advances in emerging technologies including energy, nano, bio, and ICTs coupled with the rise in genetic engineering and cognitive sciences will influence the quality of human life and societal outcomes (Roco, 2004). Therefore, understanding how technology impacts upon human decision-making and behaviour has implications for responding and adapting to future risk and uncertainty. Yet the feedbacks between technological performance and human decision-making are not well understood. Technology and behaviour are typically assessed as discrete non-interacting phenomenon, whether it is technological change modelled by differential equations (Bass, 1969) or decision theoretic models based on representative rationale decision-makers (McFadden, 1974). But there is inherent uncertainty and feedback between social, technological and physical processes not well captured by conventional approaches. Part of the challenge in modelling complex dynamical systems involves a hierarchy problem where model output resolution, and therefore understanding of a system across multiple states diverges between mean-field and agent-based approaches. Responding to those challenges, advancements have been made in systems modelling using optimization (Brede and de Vries, 2013) and multi-agent methods for assessing complex human–environmental interactions (van Oel et al., 2010; de Almeida et al., 2010; Smajgl et al., 2011; Filatova et al., 2013). Disaggregated approaches have also been used to model behaviour and networks showing the importance of assessing multiple scales of interaction (Caillault et al., 2013; Gerst et al., 2013; Schreinemachers and Berger, 2011). But there is further need for new analytical frameworks that focus on coupled dynamic interactions between technology and behaviour, better able to capture real world phenomenon (Barabási, 2005, 2009; Vespignani, 2009).

From a theoretical perspective there is scope to integrate techniques from decision theory, networks and dynamical systems to

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further our understanding of a broad range of complex socio-technical systems, characterised by heterogeneous technology and behavioural interactions across multiple system states. Here we develop a general theoretical and methodological approach termed techno-behavioural dynamics focussing on the networked interactions between technological systems and agent behaviour. We provide a case study of emergent technology to assess feedback between state dynamics, and argue for the advantages of applying both mean-field and agent-based methods within a flexible modular framework, enabling complimentary analytical resolutions. The paper proceeds with 1) methods and materials, 2) model outputs and discussion, and 3) conclusions.

2. Methods and materials

2.1. Techno-behavioural dynamic approach

Environmental and sustainability analyses are often informed by computational modelling and framed in scenarios to assess impacts and alternative strategies. Alternative strategies typically depend on technological interventions to mitigate future impacts. More recently there has been recognition of the importance of behaviour, lifestyle and other demand-side factors for mitigation and adaptation. This has led to a divergence in supply and demand side approaches in sustainability analyses. We propose an integrated theoretical and methodological approach to address some of those challenges. Scenarios are often used as a complimentary measure to mathematical modelling and simulation to ensure internal logic and consistency for model parameterization. The overarching goal of scenario analysis is to account for inherent unpredictability in various future trends. Scenarios are not predictions but exploratory visioning exercises to consider future pathways that break from current trends (Schwartz, 1998). Fig. 1 shows scenario archetypes typically used in sustainability modelling including: 1) status quo, 2) technological optimism, and 3) behavioural change. We integrate key elements from 2 to 3 to develop a new framework termed 4) techno-behavioural dynamics.

Status quo – reflects a baseline scenario typically used as the starting point in a scenario building exercise and used to compare against the assumptions and simulation results for other scenarios. It usually relies on extrapolating historical and current macro level trends. It is typically assumed that there is not a strong policy or industry initiative to induce significant change on either the supply (technological innovation) or demand (end-use) side, hence the continuation of current trends (IEA, 2008).

Technological optimism - characterizes scenarios that generally focus on advanced technological solutions to societal and environmental challenges. There is often an assumption that rapid technological deployment will be supported by a strong emphasis on supply-side industry investment and radical policy support (IEA, 2010). These scenarios typically do not explicitly account for heterogeneous agent behaviour. There is often an assumption that the future reduction in cost of technology, extrapolated from historical technology learning rates is the central mechanism for widespread adoption. While technological learning rates are more appropriate for supply-side technologies that have little interaction with human behaviour, it does not account for demand-side technologies more dependent on behavioural factors that influence adoption and end-use. Nevertheless, these scenarios were the first to take a problem solving approach and show the technical potential in mitigating environmental impacts (IEA, 2008, 2010; Skea et al., 2011).

Behavioural change – is a response to the conventional focus on technological solutions without social context. This approach is characterised by a focus on demand-side behaviour such as the reduction in energy end-use or vehicle kilometres travelled (Anable et al., 2012; Hickman and Banister, 2007). Those reductions are often based on the premise of dramatically changing normative behaviour through policy or other economic interventions i.e. price signals. There is often an assertion that end-use behaviour will have to radically change to meet sustainability objectives, but no mechanism is given as to how that change might arise, particularly at the individual level. The approach is more focused on overall lifestyles, consumption patterns, and normative practices (Anable et al., 2012; Eyre et al., 2010). Nevertheless, these types of scenarios highlighted the important role of end-use behaviour, recognizing that technology is an important, but insufficient means to achieve sustainability. Although the importance of behavioural change has been well argued, the approach typically lacks a mechanism for change, and has not accessed well developed analytical tools for decision-making and strategic behaviour found across social and biological disciplines (Jackson and Yariv, 2010; Nowak and May, 1992; von Neumann and Morgenstern, 1944).

Techno-behavioural dynamics – integrates key elements of technological optimism and behavioural change, but is embedded in dynamical systems, network and decision theory. This approach implies a simultaneous emphasis on both supply and demand-side factors i.e. technological performance, and end-use demand patterns. Specifically it focuses on individual level decision-making and how heterogeneous micro-level behaviour can scale up to influence systems performance. This approach views technology and behaviour as a coupled dynamical system co-evolving over time. With the rise of ubiquitous emerging technologies, these co-evolutionary processes will become increasingly prevalent throughout society (Barabási, 2005; Roco, 2004; Vespignani, 2009, 2012; Watts, 2007). This approach seeks to understand how individual behaviour and technologies interact, and influence each other over space and time. Importantly, the approach considers how technological performance feeds back on end-use behaviour, which in turn can positively influence continued use and technological change, leading to a co-evolutionary process. This departs from current approaches that view technology and behaviour as discrete non-interacting systems. Moreover, it is different from the literature on behavioural change that does not propose underlying mechanisms for changing individual behaviour, and also departs from the transitions literature (Rip and Kemp, 1998; Smith et al., 2005), which takes a far broader view of sociotechnical systems incorporating firms and institutions, while our focus is on

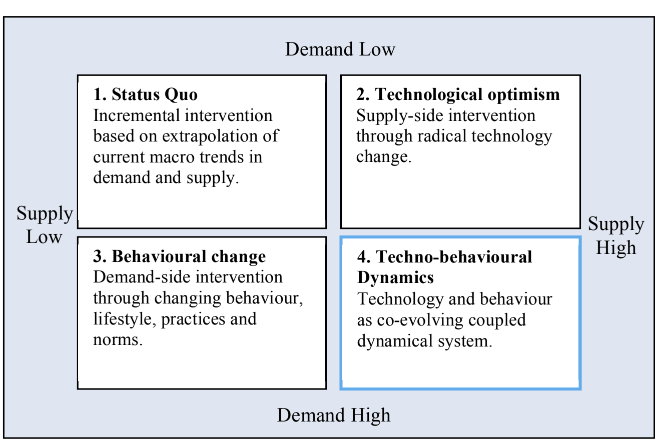

Fig. 1. Techno-behavioural dynamic framework informed by scenario archetypes. The different levels of demand and supply indicate the conceptual focus typical for each scenario. During scenario development this translates into assumptions on what key interventions will influence the trajectory and composition of the system.