A Conceptual Framework for transition modelling

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Abstract: This paper presents a Conceptual Framework (CF) for analysing and simulating transition dynamics (or radical systemic innovation) that is broadly consistent with both empirical evidence and current theorising about transitions. The framework distinguishes between a dominant socio-technical regime and a number of socio-technical niches. The central feature of the framework is to describe how niches and regime interact to produce a transition dynamic involving either a transformation or a total overthrow of the dominant regime. We base the analysis on reviews of patterns observed in historical transitions, and provide a framework for analysing the processes involved in producing future 'sustainability transitions'.

Keywords: transitions; Conceptual Framework; CF; agent-based model; sustainability assessment.

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1 Introduction

There is currently a growing interest in socio-technical transitions in the context of debates about how modern industrial societies can achieve a sustainable development. Understanding transitions is especially important when dominant ‘solutions’ (and the socio-technical systems that deliver these) contribute to unsustainable development and when novel solutions might offer more sustainable alternatives, or when we face

persistent problems that cannot be solved using only the currently dominant solutions. The context for this paper is research supporting the development of tools for analysing future 'sustainability transitions', which are important elements of the took-kit for implementing Integrated Sustainability Assessment.

In the context of debates about sustainability, we are interested in understanding the processes and patterns of competition among established and novel solutions to questions of production and consumption. We are interested in how novel and radical solutions emerge (as socio-technical 'niches') and become sufficiently powerful to challenge and, ultimately, overthrow a dominant solution (the prevailing 'regime' of production and consumption including the associated practices and set of actors) resulting in a transition. Other patterns of transition are also potentially important, including those involving a radical overhaul of the structure and practices of a dominant regime, which maintains the power of the dominant actors but nevertheless provides for a new 'solution' to take over with radically different features and performance.

Transition models are potentially important tools for understanding, assessing and supporting transition processes. However, some features of transition processes and underlying patterns, such as threshold effects, lag effects, path-dependency, and interaction across scale levels require novel modelling concepts. Most of the current modelling concepts cannot handle these key features of transition processes because they are rooted in an incremental paradigm rather than a transformative paradigm (Rotmans, 2006). Developing prototypes of such modelling tools was one of the aims of the EU-funded MATISSE project; however, this depended on first developing a framework of concepts capable of describing the essential features of transition processes and patterns (in a format suitable for implementation in a computer simulation model). Therefore, this paper presents a Conceptual Framework (CF) (referred to as 'the CF') for analysing socio-technical transitions that is consistent with both empirical evidence and current theorising about 'transitions', while also being suitable for implementation in the form of a computer simulation model.

To achieve this, we draw on a recent typology of transition patterns (Geels and Schot, 2007) to identify features of transitions that have been observed through empirical work on historical transitions. Importantly then, this typology provides us with a useful summary of the available empirical evidence about the diverse patterns observed in historical socio-technical transitions. The patterns observed in future socio-technical transitions may be different of course (not least because the sustainability imperative arguably means that society now needs to make unprecedented 'choices' about transitions). However, this was a pragmatic and feasible way to feed an overview of the available empirical evidence into the development of the CF. In addition, extensive use was made of other empirical and conceptual work on socio-technical transitions in developing the CF (see for example Geels 2005b; Rotmans 2005).

We use concepts from the literature on socio-technical transitions to develop a narrative about the kinds of processes involved in producing transition patterns. Fundamentally, we conceptualise a transition as arising out of a dynamic interplay between a dominant (or 'incumbent') regime and a set of competing niches. We identify a minimum set of 'mechanisms' that could, in principle, reproduce the features of observed transitions and suggest how these might be represented operationally within a transition model.

In addition, we define a background socio-technical 'landscape' that represents underlying, but powerful, currents that inexorably change the context of opportunities,

challenges and problems facing both the regime and niches. Through differentiated response 'mechanisms', we conceptualise how landscape 'signals' can either favour the regime, and stability, or niches, and an eventual transition. The result is a structured narrative about the kinds of processes involved in producing observed (and possible future) transitions.

The remaining sections of this paper are organised as follows: Section 2 sets out the way in which we conceptualise the regime and niche as sub-systems and, building upon this, how we conceptualise a transition and how we define relations between niche, regime and landscape; Section 3 describes how we conceptualise the internal functioning of the regime and niche sub-systems; while Section 4 presents a set of mechanisms for 'simulating' the dynamical interactions between regime and niche sub-systems; finally, Section 5 provides a conclusion.

2 Overview of the key features of the Conceptual Framework (CF)

2.1 Both regime and niche are conceptualised as interacting sub-systems

We base the CF around the opening gambit of conceptualising both niches and the regime as systems – or specifically as 'sub-systems' (within the overall context in which a specific transition may occur). Three 'types' of sub-systems are defined: regime (R), niche (N), and an empowered niche (EN). The EN represents a niche that has grown 'powerful' enough to gain a number of new characteristics, most important of which is the ability to attack (sometimes effectively) an incumbent regime (and therefore to potentially take over from it).

The theoretical point of departure for the CF is the literature on socio-technical transitions (for example, Geels 2005b; Rotmans 2005). We also draw upon the conceptualisation of structures, actors and practices found in social theory, in particular the structuration theory of Giddens (1984) and the social systems theory of Luhmann (1995, 2002).

We conceptualise the dynamics of societal processes as involving a mutual interplay between structures, actors and practices; a transition consists of a dynamic that leads to a fundamental change in these structures, actors and practices. Structure is recursive; it is both the result and means of acting. For our purposes, we use a broad conceptualisation of structure, it includes physical assets and infrastructures, as well as rules, regulations, institutions and norms, which act in multiple ways upon actors to facilitate the continual reproduction of a set of practices.

Practices are, therefore, defined in terms of the actions or behaviour of actors. Because this work is aimed at conceptualising 'sustainability transitions', we are interested not just in technological practices but in 'technical' and 'social' practices in the broadest sense. This is because we assume that many of the changes in practices required in a particular 'sustainability transition' may involve not only changes to new technology but also fundamental changes in 'lifestyles' or social practices. Thus, to illustrate with an example, we are interested not just in a change from a petrol vehicle to a hydrogen fuel-cell vehicle, but also in changes of practice from car ownership to car pooling, or from car use to walking (and other 'slow modes' of transport).

Following Giddens (1984), we conceptualise structure as forming the condition (or framework) within which actors exhibit agency. Structures will tend to maintain

practices, which are reproduced, but can also be changed, through the behaviour (agency) of actors working individually or collectively. Here, we are interested in providing a CF that is helpful in understanding how the tension between structure and agency may play out in empirical examples of transitions, and in particular how the balance may be different in a niche vs. the regime.

A 'regime' is usually understood as a constellation of 'dominant practices, rules and shared assumptions', which act as a homogenising influence on actors (e.g., van den Hoed and Vergragt, 2004). Here, we use the term 'regime' to refer to the 'regime sub-system' and define it as a construct, which represents not only the dominant set of practices, but also the actors and structures associated with that dominant set of practices. So, the peculiarity of our framework is that the behaviour of many actors is aggregated within the construct of a 'regime'; thus, in Section 4, we will define specific 'adaptations' or 'adaptive behaviours' on the part of the regime, which describes the 'emergent' outcome of the behaviour of many individual actors.

The regime's cognitive, normative and regulative institutions act to establish and reinforce stability and the cohesion of societal systems. But they can also tend to limit innovation in practices to localised, incremental improvements (Geels, 2005b). Transitions research has identified 'niches' – individual practices and actors outside or peripheral to the regime – as the loci for radical innovation (Geels, 2005a, 2005b; Rotmans et al., 2001; Rotmans, 2005; Smith et al., 2005).

A socio-technical 'niche sub-system' (referred to as a 'niche') is understood then as being broadly the same type of sub-system (as the regime sub-system). It consists of a constellation of practices, rules and shared assumptions associated with a particular set of actors who are active in the niche (as well as the actors themselves and associated structures). For any particular transition example, we allow the possibility of many niches and EN s, but only one or zero regimes.

Both the niches and regime are associated with particular 'structures'. However, crucially, we also assume that niches will be subject to, or have access to, the structure of the dominant regime. Thus, under certain circumstances, the niche may be able to 'free ride' on the infrastructure of the regime (for example, by making use of an existing physical infrastructure to deploy a new technology). In other situations, this may manifest as a constraint, with the ability of the niche to be 'innovative' being constrained directly by the regime. The extent to which the niche can make use of the existing structures of the regime depends on the specific empirical example being addressed – within the CF we allow for a full range of possibilities. This 'control' (of the niche on the part of the regime) can potentially take many forms and has the effect of constraining the opportunities and competitiveness of the niche in terms of, e.g., its ability to produce and market products and services, its ability to reach and influence consumers, its ability to influence key actors and networks (such as the political system).

Defining the niche and regime as sub-systems represents a way of conceptualising the dynamics of niche–regime interactions without needing to explicitly resolve every actor involved. Our aim in doing this is to provide the basis for a new type of transition model that is 'relatively simple' but with just the right degree of complexity to capture the major features of the dynamics of a transition. The highly complex make-up of the many different regime actors, and the associated practices and structures, is abstracted as a construct called the 'regime' sub-system. This allows the further elements of the CF to be defined in terms of:

- the interactions between sub-systems
- the interactions between sub-systems and the background socio-technical 'landscape'
- the internal functioning of each of the sub-systems.

Thus, rather than attempting to describe 'behaviour' at the level of each individual actor associated with the regime, we instead define a set of abstracted 'mechanisms' that approximate the outcome of the 'behaviours' of many individual actors. These 'mechanisms' describe the emergent 'adaptations' and 'behaviours' at the level of the regime (or a niche). As will be described in Section 4, we develop this set of mechanisms based on 'patterns' observed in historical transitions.

We apply the terms 'adaptation' and 'behaviour' to the regime and niches, but with the recognition that this represents an abstract representation of the behaviour of many individual actors, who in most cases will not be acting explicitly with a unified purpose and who may not even identify themselves as belonging to a 'regime' or 'niche' (although for some current socio-technical niches, this reflexive aspect of self-identification as niche may indeed be an added element of complexity). However, we do wish to capture how 'emergent' properties at the level of the regime can then affect the behaviour of individual actors. Thus, in developing simulation models based on this CF, we are interested in being able to capture a recursive dynamic whereby the behaviour of multiple actors leads to emergent properties at the level of the regime (or niche), which then in turn feed back to lower scale levels (to effect the behaviour of individual actors). We hypothesise that capturing this type of recursive dynamic is key to successfully reproducing the highly non-linear dynamics associated with socio-technical transitions.

For each sub-system, the CF defines a representation of the 'internal functioning'; this describes the 'logic' of production and consumption resulting from the set of actors, dominant practices and structures associated with that sub-system (see Section 3). This internal representation also addresses the processes by which practices are maintained (or allowed to change) over time.

Crucial to our approach is the hypothesis that the way to proceed with modelling transition dynamics is to produce relatively simple models that can eventually be used as heuristics or 'learning tools' in a decision-making context (explorative tools rather than forecasting tools). The model is used as part of a 'dialogue' among a group of stakeholders who are trying to understand a (potential) transition and how to support it. The device of conceptualising transitions as a dynamic interplay between regime and niche sub-systems leads (potentially) to relatively simple models (suitable for use in decision-making contexts). In some cases, however, the behaviour of specific actors may be of crucial interest for understanding the dynamics of a transition (and the potential for supporting a transition); hence, we also include the possibility of a detailed representation of specific actors and actor groupings (such as consumers or political actors, see Section 3.3).

2.2 Definition of mechanisms, transition patterns and pathways

In the CF, we define the following hierarchy of terms in order to deconstruct any particular transition pathway (de Haan and Rotmans, 2007):

- By *mechanism.* We refer to an identified societal process, which is important to the core dynamics of regime change; mechanisms are triggered either by certain changes in the landscape or by interactions between two sub-systems (e.g., clustering of niches, adaptation of regime to landscape changes); or through the internal dynamics of a sub-system.
- A *transition pattern*. Can be identified as a particular (minimal) combination and sequence of mechanisms that commonly occur in socio-technical transitions (see Tables 1 and 2).

Table 1 Typology of transition patterns

Transition pattern	*Main actors*	*Type of interaction*	*Empirical examples*
Transformation	Regime actors and outside groups (social movements, scientists and regulators) who 'translate' landscape pressures	Regime outsiders voice criticism, inducing adjustment of regime goals, search heuristics, etc. Regime experiences institutional power struggles and negotiations Minimal involvement of niche/s	Dutch hygienic transition from cesspools to sewer systems between 1850 and 1930 (Geels, 2006a)
De-alignment and re-alignment	New niche actors	In response to landscape pressures, incumbents lose faith and legitimacy. Regime is eroded and collapses. Emergence and competition of many new actors and novelties. Prolonged uncertainty, followed by dominance of one niche, and restabilisation Niches in *competitive* relationship	Transition from horse-drawn carriages to automobiles in the USA between 1870 and 1930 (Geels, 2005b)
Technological substitution	Regime actors vs. niche firms	Radical innovations develop in protected niches; regime remains stable. Landscape shocks/pressures destabilise the regime, and create windows of opportunity for niches to compete with the regime and increase market share through niche-accumulation. New technology may lead to wider societal changes Niche and regime in (market) *competitive* relationship	British transition from sailing ships to steamships (Geels, 2005b)
Reconfiguration	Regime actors and niche actors in symbiotic relationship (e.g., suppliers)	Niche component-innovations adopted by regime actors. Competition between old and new suppliers. Cumulative component changes and new combinations result in new regime architecture, and triggering wider changes e.g., new user practices and perceptions Niche and regime in *symbiotic* relationship	Transition from traditional factories to mass production between 1850 and 1930 (Geels, 2006b)

Source: Adapted from Geels and Schot (2007)

Table 2 The set of 'mechanisms' defined in the CF and a specification of their role in a set of four different transition 'patterns'

	Transition patterns (*based on Geels and Schot, 2007*)			
Mechanism	*Transformation*	*De-alignment/ re-alignment*	*Technological substitution*	*Reconfiguration*
Transformation				
Transformation (T_1): Niche to Empowered Niche	No	Yes – multiple competing empowered niches (ENs)	Yes	No
Transformation (T_2): Empowered Niche to Regime	No	Yes – eventually, one EN dominates others	Yes	No
Transformation (T_3): Regime to Empowered Niche	No	Yes	Yes – regime may persist as a 'relic'	No
Emergence, growth and clustering of niches				
Emergence of niches	No	Yes	Yes	Yes
Growth (or decline) of niche or regime	No	Yes	Yes	New components gain importance; old ones lose importance
Niche clustering	No	Yes	Yes	No
Adaptations of the regime and niche sub-systems				
Adaptation: adjust resource allocation within a sub-system	Yes	No	Yes	Yes
Adaptation: maintenance of practices	Yes	Yes	Yes	Yes
Adaptation: changing practices	Yes – through external pressures and internal negotiations	No – landscape pressures too great; regime collapses	Yes – incumbents invest in product improvements in response to niche threat	Regime gradually substitutes current practices for Niche practices (1)
Adaptation: absorption of a niche by the regime	Perhaps – only if symbiotic	No	No	Yes – if symbiotic
Adaptation: competition with the regime	No	No (2)	Yes	No
Adaptation: attempt to influence landscape	No	No	No	No

1: Each initial substitution of components (as practices or groupings of practices) from the regime may then lead to further adjustments and re-combinations of practices.

2: The regime collapses in response to pressure from the landscape, not competition from an Empowered Niche; there may be competition between Empowered Niches however (leading eventually to the emergence of a new dominant regime).

- A transition pathway results from a transition pattern plus a start-point and end-point; so the transition pattern is composed of a description of a sequence of mechanisms, whereas a transition pathway includes this but, in addition, describes the initial state of the system and the 'end' state of the system. Of major importance to our work on sustainability transitions is the need to explore a transition pathway in order to make statements about whether a particular transition has resulted in a more or less 'sustainable' state.

Thus, two key functions of the CF include: identifying the minimal set of mechanisms required to generate a range of different transition patterns, and describing their operation, including the important sequencing issues (e.g., in terms of which mechanisms have to be triggered after each other to produce a regime change).

2.3 A transition is defined in terms of niche-regime dynamics

We conceptualise the dynamics of a transition as involving tensions between the regime and its environment (both from the landscape and niches) out of which threats may arise to the currently dominant regime and a response (or no response) on the part of the regime. The regime may be threatened from the niche level, or from changes at the broader 'landscape' level of economic, ecological and cultural trends, or from internal misalignment amongst regime actors (Geels, 2005b). Once a threat is recognised, regime actors will mobilise resources from within the regime, and in some cases from within niches, to respond to it (Smith et al., 2005; Geels and Schot, 2007); a range of different responses can be identified in the empirical evidence base. Thus, the dynamic interplay of niches and a regime provides us with the basis for describing the core dynamics behind a transition.

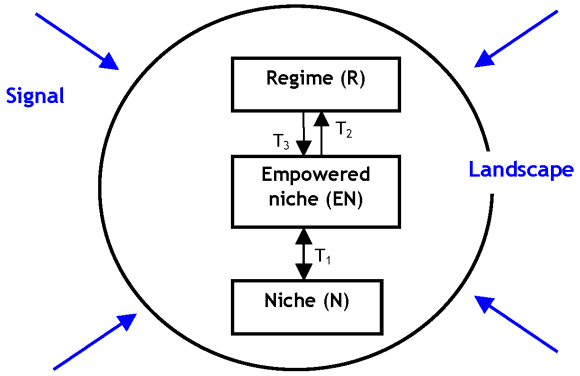
For the purposes of the CF, a (socio-technical) transition is defined as a fundamental change in the (socio-technical) regime; in other words, a radical shift in a system's dominant structure, actors and practices (Loorbach and Rotmans, 2006). A transition may involve a transformation of the incumbent regime or a complete replacement of the regime, and typically occurs over decadal time scales. Naturally, this process is composed of many incremental steps, but may also involve catastrophic events or 'tipping points' (e.g., Gladwell, 2000). By a 'fundamental change', we refer to a 'system-exceeding change', i.e., a change that goes beyond the ordering of the current system, which implies an element of irreversibility.

A key dynamical pattern captured in the CF is thus the process of transformation of first a niche (N) into an empowered niche (ENA), and then an empowered niche into a new dominant regime – as represented in Figure 1. In certain types of transition (e.g., 'technological substitution' pathway, see Section 4), a transition is associated with this process of overthrowing the incumbent regime. In other types of transition (e.g., 'reconfiguration' pathway), niches may be absorbed or combine with the regime. Thus, *both competitive and symbiotic relationships between the niche and regime are possible* (Geels and Schot, 2007). A transition implies a fundamental change in regime (i.e., transformation or replacement), and thus a shift in power.

The CF draws upon a *Multi-Level Perspective (MLP)* on transitions (Kemp and Rip, 1998; Geels, 2005b), which defines three functional levels comprising micro ('niche'), meso ('regime'), and macro ('landscape') (Kemp and Rip, 1998; Geels, 2005b). Building on this MLP, the CF describes three functional levels of sub-systems and a fourth

functional level in the form of the background socio-technical landscape. Figure 1 shows the relationships between the sub-systems (regime, empowered niche, niche), and their interactions with the landscape (through resource flows, and through feedbacks to structures and practices). So, we have actually four levels: that of a niche, an empowered niche (a sort of niche-regime), a regime and a landscape. The different functional levels of sub-system are all 'embedded' within the wider socio-technical landscape.

Figure 1 Sub-systems (regime, empowered niche and niche) interact with each other and with the landscape (through landscape 'signals'). Transformations of niche to empowered niche (T_1), empowered niche to regime (T_2), and regime to empowered niche (T_3) can occur



In the CF, the three functional levels are realised in terms of

- the relationships allowed between the different types of sub-system
- through differentiated responses to landscape signals
- through certain unique properties assigned to each sub-system type.

We do not define a specific hierarchy (in systems terms) between the different types of sub-system, rather the ways in which the regime influences a niche (and vice versa) emerge uniquely in each specific application of the framework to an empirical example.

It is expected that the structures associated with the regime will (to a certain extent) constrain the practices of a niche (but this is not a prerequisite of the CF). Some niches may exist very close to the regime, and therefore both benefit from the support of the regime and be constrained by it; while other niches may be protected from the influence of the regime in some way (e.g., through the support of political actors at the landscape level).

3 A description of the 'internal functioning' of niche and regime sub-systems

All sub-systems (i.e., regime, empowered niche, and niche) are conceptualised as having an internal dynamics. The first type of internal dynamics that we wish to capture is the way in which a sub-system may grow in 'size' (and 'influence') over time, or endure a long period of stability, or go through a period of gradual (or rapid) decline.

We are interested in the effect that such patterns can have on the dynamics of niche–regime interactions (and therefore transitions); we also want to capture the way in which gradual (or abrupt) changes in the landscape can affect the viability of a niche or regime. Capturing this type of dynamic requires some adequate representation of the 'logic' of production and consumption associated with the regime and a representation of how it relates to the 'logic' of production and consumption of niche sub-systems and events in the landscape.

A second type of internal dynamics that we wish to capture relates to the ability of the sub-system to maintain or change 'what it does' over time; we are interested then in how (and under what conditions) a sub-system can maintain a certain set of practices over time, and how (and under what conditions) these practices may change. Where practices are changing over time we need then (through our representation of the 'logic' of production and consumption) to be able to simulate how this affects the 'viability' of the sub-system as a whole. Viability is defined in economic terms (market share, competitiveness, etc.), but also in terms of the 'support', which actors may give to a niche or regime in other ways (such as political support as 'voting' or behaviour that supports a particular practice). Some changes in practices will make a sub-system less viable while some will make it more viable.

3.1 Generation and use of resources

The purpose of resolving the resource generation within the sub-system is to capture how the regime (or niche) may grow or decline over time, and the implications of this growth (or decline) for interactions with other sub-systems and the landscape. Specifically, we want to capture how resource generation interacts with niche–regime dynamics. For example, a niche that is able to sell an increasing amount of a product may be able to 'grow' until it becomes sufficiently large to threaten and then take over from the regime. The practices associated with each niche or regime may become more or less able to generate resources as changes occur in the landscape. The resource generation model needs to resolve resource generation as a function of a set of practices.

For a socio-technical regime, the resource flows that may (potentially) be represented include: the flow of financial resources, the flows of physical resources (material flows) and energy, and the flows of information (and knowledge).

Next, we sketch a very simple representation of resource generation; however, we see the CF as being consistent with using a wide range of different modelling approaches to supply this *particular element* of the overall dynamics. Resources are generated as a function of practices, support (through e.g., consumers buying a product) and the current physical capacity (representing, e.g., infrastructure and production capacity). Resources are then used to grow and maintain 'structure'. The structure is resolved as consisting of a 'stock' (in systems terms) – one representing institutional capacity and one representing physical capacity. These stocks have a maintenance cost and can depreciate over time (so the niche or regime needs to generate a certain level of resource just to maintain its current size). The institutional capacity is conceptualised as representing the ability of the regime or niche to exert 'influence' (over other sub-systems).

An important feedback is between physical capacity and resource generation: if a sub-system invests in expansion of physical capacity (e.g., factories), it is able, in turn, to generate more resources (e.g., cars); and conversely, depletion of physical capacity

diminishes resource generation. An allocation rule can be used to represent the proportion of resources generated that go into generating physical vs. institutional capacity.

Various other activities that a sub-system may engage in will also involve a resource cost. For example, changing the practices associated with the regime (through adaptation) may involve a resource cost (e.g., investment in new manufacturing equipment); attempting to influence consumers through marketing involves a resource cost.

Importantly, this representation needs to capture how the internal functioning of each sub-system is related to the other sub-systems and the landscape. Market dynamics are captured because 'consumers' are able to shift their 'support' from one sub-system to another (see Section 3.3), thus allowing shifts in market share over time to be captured. More fundamental changes in the nature of the market can also be captured as a niche (or the regime) may change its associated practices over time and consumers may change their preferences for certain practices. The 'mechanisms' defined in Section 4 also allow the possibility for market manipulation as a sub-system influences the 'rules of the game'. Elements of institutional and political dynamics (and their influence on niche–regime dynamics) are also captured through the mechanisms described in Section 4, which, in turn, make use of the internal systems representation described here.

3.2 Representation of structures and practices

The second important aspect of the internal dynamics of each niche (or regime) sub-system is how the CF represents the way that practices, and the structures associated with these practices, change over time.

We conceptualise the regime as attempting a 'self-maintenance' of practices over time (even in the face of changing landscape conditions). Self-maintenance then means the maintenance of specific practices and also the structures that are consistent with these practices.

This maintenance of practices may continue in the face of both changes in the landscape and/or pressure from other sub-systems. However, in response to significant landscape changes (or a major 'threat' from another sub-system), the sub-system may also seek to adapt, and actively change its practices. The adaptive 'mechanisms', we define to handle the maintenance (or change) of structure and practices are described in Section 4; here, we describe the conceptual framing of the representation of structure and practices within each sub-system.

Structures are conceptualised as consisting of both a physical and an institutional capacity; both of which are oriented towards supporting a particular set of practices. Therefore, in attempting to shift to a new practice, the sub-system faces a number of problems. First, there is the issue of whether that new practice is available to that niche or regime sub-system. Here, there are a number of possibilities: the practice may be easily available; the practice may only be available to a particular niche and not to the regime (or vice versa); the practice may not be fully developed yet and may therefore require investment in 'research and development' to make it available to the regime. Second, even if the practice is available (or can be made available) to the regime (or niche), there is still a cost associated with re-aligning structures (both in terms of institutional and physical capacity).

There is a possibility of there being a 'misalignment' between structure and practices with a resulting loss of efficiency (in terms of, e.g., the ability to generate resources) and therefore 'viability'. Importantly, the interplay of structure and practices described here

defines the challenge that a sub-system faces in attempting to shift towards new practices (i.e., not only practices themselves but also the concomitant structures need to adapt). To develop the concept of alignment between structure and practices, we define a mechanism by which they can be more or less aligned. An external intervention may act to change a certain practice but the associated structures remain unchanged; then when the external pressure is removed, structures act to reassert the previous practice(s).

In our stylised description of a 'stable' regime, structure and practices are associated with the same 'type of activity' and they interact so as to continually reproduce one another. If there is a misalignment between practices and structures, the regime will try to correct this. Misalignment between structures and practices ('instability') reduces a sub-system's capacity to generate resources. This, therefore, weakens the sub-system. Regime instability is a significant precursor to a transition, particularly in the 'de/re-alignment' pathway (see Table 1). The regime may also become weakened by losing 'support' (as described in Section 3.3).

3.3 Resolving the behaviour of individual actors within a sub-system

As we have seen already, the regime (or niche) sub-system aims to implicitly capture the emergent 'behaviour' arising from the activities and actions of many diverse actors with that sub-system. As already explained, this device greatly simplifies the complexity inherent in a real-world socio-technical transition example. But what if there are specific groups of actors (or indeed significant individual actors) who may have a very strong influence on the dynamics of a transition? Resolving them explicitly may then be important to understanding the dynamics of a particular transition. An example would be consumers switching en masse from a product or service produced by the regime to one produced by an emerging niche. The consumers might be responding to a strong landscape signal or they might be responding to an internally driven change in preferences over time.

Within the CF, we wish to allow for the possibility of starting with a 'simple' model that resolves only the regime and a few niches and then progressing to also resolving consumers explicitly (and/or selected political actors and/or selected corporate actors). The extent to which they might have a critical role to play in the dynamics of a transition can then be a question to be explored in model experiments. Importantly, this approach allows more conventional 'agent-based' models to be embedded within the overarching framework described in this paper (Schilperoord, 2005).

We use the concept of 'support' to describe the effect of individual actors (such as consumers) supporting a particular niche or regime through either material exchange or social or cultural validation in some way. This might be, for example, consumers purchasing a product such as a car from the 'regime', and then over time switching their purchases to a product produced by a growing 'niche'; in the CF, this is represented as a shift in support from the regime to a niche.

Both the niche and regime are defined in terms of the specific practices that they are associated with. Preferences for certain practices are assigned to consumers (with some distribution in these preferences across the set of all consumers). A representation of how consumer preferences may change over time in response to various internal and external stimuli can then be used. Such a 'consumer module' should capture how consumer preferences respond to: pressure from the regime and niches (e.g., marketing); landscape signals (e.g., climate change impacts, increasing oil price); or dynamics internal to the

sub-system or consumer grouping themselves. The interaction is then two-way as the decision-making of the consumers (modulated by their preferences) affects the support obtained by the regime (and thus its continued viability) while the regime in turn attempts to influence consumers.

4 Description of the niche-regime dynamics underlying a transition

We now come to the central task of the CF, which is to address how a socio-technical transition might be described as 'emerging' through a set of 'mechanisms' that describe the underlying dynamic interactions of the regime, niches and landscape.

The aim is to identify and then frame these mechanisms in a form that can be implemented in a computer simulation model. This facilitates a parallel process that explores how observed transition patterns can be simulated starting only from the use of this set of mechanisms to describe the allowed dynamical interactions.

We conceptualise a transition as arising from:

- the dynamic interplay of the regime and niches
- their differentiated responses to events and ongoing change in the landscape
- the internal dynamics of the niche and regime
- interactions between any combination of the first three elements.

Furthermore, as described in Section 3, certain key actors within the niche or regime (such as consumers or political actors) may be resolved as part of a representation of the internal functioning of the niche and regime.

Using a typology of observed transition patterns

We identify a minimal set of mechanisms, which are required to describe the sequences of mechanisms that constitute each of Geels and Schot's patterns. The Geels and Schot typology is based on the MLP, which sees transitions as the product of interactions between the niche, regime and landscape levels (Kemp and Rip, 1998; Geels, 2005b). The nature and timing of these interactions give rise to different types of transition, as outlined in Table 1.

Other typologies of transitions have been developed. For example, Berkhout et al. colleagues (2004) categorise transitions into four 'types' using two dimensions:

- availability of resources (factor endowments, capabilities, knowledge)
- degree of coordination of resource deployment (unplanned/emergent vs. planned/vision-driven).

Geels and Schot acknowledge similarities between their typology and that of Berkhout et al., but highlight the different types and timings of regime interactions with niches, which are explicit in their work, but are not distinguished by Berkhout et al. Another typology of transitions is developed by Rotmans (2005). This distinguishes between transitions, which are

- goal-oriented or emerging
- require more or less coordination
- are aggregated or not.

The set of mechanisms described here has been developed then with the specific aim of being able to simulate the Geels and Schot transition patterns. However, in parallel work we are using the same basic approach to extend the CF to address additional typologies of transition patterns (de Haan and Rotmans, 2007).

In the following sections, we provide a short narrative description of each of the mechanisms that we hypothesise might be sufficient to simulate or 'mimic' the dynamics for the different transition patterns as defined by Geels and Schot. Table 2 summarises the mechanisms (rows) and indicates which mechanisms are present in each 'type' of transition (columns) – based on our interpretation of the evidence from observed transitions that is summarised in Geels and Schot and the literature cited therein.

4.1 Transformation of the niche and regime sub-systems

Transformation describes the mechanism by which one type of sub-system changes into another type of sub-system. We do not conceptualise this change as involving a fundamental change in the nature or functioning of the sub-system, the basic structure and functioning remains unchanged; however, certain unique (emergent) behaviours are associated with each type of sub-system. The transformation mechanisms are defined here as simple threshold effects.

4.1.1 Transformation of Niche (N): Empowered Niche (EN): T_1

A niche will automatically transform to become an empowered niche once it reaches a certain critical 'size' as measured in terms of its 'institutional capacity'. The institutional capacity is a property of the niche that can grow or decrease over time (see Section 3); it is defined as being a measure of the niche's 'ability to influence' the regime. However, modelling work could also experiment with alternative formulations of the 'ability to influence', which might, for example, include a measure of the 'support', which the niche receives from consumers and other actors. The niche may grow to a sufficient size through internally driven growth (see Section 3) or through clustering events with other niches (see below). The essential difference between a niche and an empowered niche is that the empowered niche is able to actively compete with (or challenge) the incumbent regime (see Section 4.3.5).

4.1.2 Transformation of Empowered Niche: Regime: T_2

An empowered niche becomes the new dominant regime, once it has a greater 'ability to influence' than the existing regime (as measured through the sub-system property of institutional capacity, see Section 3). The regime is downgraded to an empowered niche with an associated 'penalty' on its institutional capacity. This transformation may also occur in the absence of a currently dominant regime, in which case it relies on the empowered niche passing a threshold in terms of its institutional capacity.

4.1.3 Transformation of Regime (R): Empowered Niche (EN): T_3

This mechanism covers the situation where the currently dominant regime becomes weakened and effectively collapses but at the same time, there is an absence of an empowered niche that is able to immediately take its place. The regime becomes 'weakened' because either it is no longer well suited to landscape conditions (and is not adapting fast enough, see below) or because of competition from niches and empowered niches. A threshold effect (defined in terms of the regimes institutional capacity) causes it to be 'downgraded' to a niche (with an associated penalty to its institutional capacity), resulting in a period with no dominant regime.

4.2 Emergence, growth and clustering of niches

Next, we describe three mechanisms that cover the emergence, growth and clustering of sub-systems.

4.2.1 Emergence of niches

In the CF, we allow the spontaneous emergence of new niches. They may emerge with any combination of practices, but are more likely to emerge where there is a 'gap' in the market or some unfulfilled societal demand (e.g., for environmental protection). This 'unmet demand' may be represented in a variety of ways. One way to represent it is through the preferences of consumers (or other actors that are individually resolved). Consumers are represented as having 'preferences' for certain practices. By 'dissatisfied', we then imply a situation where the current set of sub-systems (both regime and niches) is unable to fully satisfy the consumers' preferences for certain practices. Where there is a higher 'density' of 'dissatisfied' consumers, niches are more likely to emerge spontaneously.

4.2.2 Growth (or decline) of sub-systems (niche or regime)

The internal representation of a sub-system (as described in Section 3) allows a niche or regime to 'grow' in 'size' over time (where size is equated with a combination of an institutional capacity and a physical capacity, see Section 3). There is a maintenance cost associated with maintaining a particular size, however. This means that, given constant conditions, the sub-system tends to grow to a maximum size (where the generation of resources matches the cost associated with the maintenance of the current size of the sub-system). Through this mechanism, and an adequate representation of the internal functioning of the sub-system, it is possible to mimic the ways in which the 'size' of the regime and niches is affected both by competition and by changes in the landscape. Competition may result in a decrease in the support experienced from consumers, thus leading to a decrease in the ability to generate resources and maintain a certain size. A change in the landscape may make a niche (or regime) less able to generate resources with a concomitant impact on its ability to grow (or even maintain a particular size). The transformation mechanisms described above all depend directly on the size and 'ability to influence' of particular sub-systems.

4.2.3 Clustering of niches

A second mechanism through which larger niches can emerge is through the clustering of niches. The clustering mechanism is invoked in a particular 'clustering event' (triggered either by an exogenous landscape signal or as a random event). There are participating criteria for niches to cluster together in such an event. We define the following possible criteria: having similar practices; having complementary practices; or both/all niches having practices that are sufficiently dissimilar from those of the regime; and/or being over a certain threshold of institutional capacity. This set of criteria has been developed based on the range of different reasons for niche clustering that we could identify in empirical examples, and simply illustrates the broad range of reasons why a clustering event may occur. For an application of the CF to an empirical example, identifying the specific types of niche clustering that might occur is an important part of being able to simulate the likely transition dynamics.

4.3 Adaptations of the regime and niche sub-systems

Here, we identify some of the most important 'adaptations' that the regime may exhibit in response to external events (or threats) from either other sub-systems or from the landscape. When we use the term 'adaptation' to describe how a sub-system interacts with other sub-systems, we are referring to the 'emergent' changes that we might expect to see in societal systems as suggested in the transitions literature (e.g., Smith et al., 2005). Such 'adaptations' at the sub-system level are the result of the many individual actors (that make up the regime) adapting in response to multiple stimuli; collectively, these individual adaptations result in an emergent 'adaptation' at the level of the regime, and it is this that we are trying to capture (or 'mimic') in the mechanisms described later. Inevitably, our descriptions of the different adaptations of sub-systems involve the huge simplifications necessary to produce a framework that is tractable to implementation in a simulation model.

4.3.1 Adaptation: adjust resource allocation within a sub-system

The regime (or a niche) may adjust the internal allocation of resources as a response to an external stimulus. This might include, for example, regime actors shifting focus to a greater emphasis on political activities (e.g., lobbying) with an associated resource cost that must be taken from other activities.

4.3.2 Adaptation: maintenance of practices

In this mechanism, the regime (or niche) attempts to maintain its current practices and associated structures. If there is a misalignment between practices and structures, the regime will try to correct this (see Section 3). Misalignment between structures and practices ('instability') reduces a sub-system's capacity to generate resources (see Section 3). This, therefore, weakens the sub-system. Regime instability may be a significant precursor to a transition, particularly in the 'de/re-alignment' pathway (see Table 1).

4.3.3 Adaptation: changing practices

Here, we describe this mechanism for the regime but it may also be invoked for a niche or empowered niche sub-system. The practices and structures of the regime may become less optimal as landscape conditions or other sub-systems change (in terms of causing the regime to generate fewer resources, which in turn can make it less able to exert influence and more vulnerable to attack). In response to this situation, the regime may (or may not) attempt to change its practices (or more precisely change the rate of change of its practices and the nature of the new practices towards which it is changing). If it attempts to change its practices, it may or may not be successful.

The idea of 'rigidity' is important here. In the CF, we want to include the possibility that, for some reason, the regime is not easily able to adapt. This can be captured by:

- limiting the range of practices available to the regime, and/or
- introducing a 'resource cost' for achieving a change of practices, and/or
- making adaptation of practices contingent on getting a 'blueprint' of those new practices by absorbing a niche (with those new practices), and/or
- allowing the regime only a limited ability to take account of landscape changes (equivalent to its having a 'blind spot' to certain external changes).

This adaptation mechanism assumes that either an external 'event' or the reaching of an external 'threshold' can be defined based on which the adaptation response of the regime is 'triggered' (as in initiated). This represents the emergence within the sub-system of an adaptive response based on the decisions and actions of the multiple (and diverse) individual actors that make up the regime (but which are not necessarily explicitly resolved within the CF, or the type of models that we proposing). The identification of a suitable 'trigger' for an adaptation can be based on the construct of:

- an explicit set of adaptation goals that the regime actors (e.g., firms, politicians) have, and/or
- an optimisation or survival algorithm (e.g., adapt to survive), and/or
- a continual searching for novelty and new markets/opportunities.

Other algorithms for decision-making will also most likely be explored in model implementations developed from this CF. As stated earlier, the aim of this CF is to provide a broad framework within which questions can be explored through model experiments rather than taking a specific theoretical position on how adaptation might emerge in a regime.

In the CF, any particular practice is associated with a corresponding structure (i.e., both a corresponding physical capacity and institutional capacity). Therefore, if a practice is changed, then the structure must be 'realigned' to fit this new practice *or* there will be a mismatch between structure and practices, which will result in a decrease in the efficiency of functioning of the regime (specifically described as an impact on the ability of the regime to generate resources and/or exert influence). Thus, when the regime (or niche) changes a practice, its structure needs to be realigned to achieve an optimal functioning of this practice and there is a one-off resource cost associated with this. Practices can be changed on a relatively short timescale (months to a few years) but

structure can take much longer to change. This introduces the possibility of maximum rates of change in the regime's ability to adapt.

For the regime, there may be other internal or external pressures that could cause structures and practices to become misaligned. For the time being, however, we only consider the issue of misalignment generated by the regime's own adaptation responses (as described above). Future developments of the CF may include a more detailed treatment of the dynamics between structure and practices.

An important feature in many historical transition examples is the process by which new product/technological functionalities emerge through 'co-evolution' between the producer and consumer (Geels, 2005a). This requires on the consumer side a mechanism by which various drivers can cause consumers to move towards new areas of 'practice space' (in a co-creation/expansion of practice space). For the producer, it requires that they are able to generate an adaptation of practices in response to observations about consumer demand (and the rate of change of consumer demand). This is a challenging concept to implement in a simulation model (although see Frenken, 2001, for one possible implementation), and is another important area where the CF could be further developed.

4.3.4 Adaptation: absorption of a niche by the regime

We identify two potentially distinct variants of this mechanism. In the first variant of this mechanism, the motivation is pure competition – the regime absorbs a niche to remove a (current or potential) threat. There may then be a resource cost associated with this absorption.

In the second variant of this mechanism, the regime 'realises a need' to change a practice, as an adaptation to a landscape change (or in response to competition from niches, or driven by its own goals or vision), and so attempts to move within the practice space towards a new practice. To do this, it may need to obtain 'blueprints' to the new practices by consuming appropriate niches (alternatively the resource cost or time-lag may be lower in taking this route rather than changing practices in a 'stand-alone' mode). In this process, it absorbs niches to 'learn' new practices. From the point of view of the niche being absorbed, we assume that it may consider this absorption a poor outcome (annihilation) or a good outcome (a chance to join the powerful players).

In implementing this mechanism, there is a need to define criteria for a successful/failed attempt at absorption, and also the resource cost associated with absorption (equating, for example, to the cost of buying up start-up companies).

4.3.5 Adaptation: competition with the regime

This mechanism covers direct competition between the empowered niche (which automatically competes with the regime) and the regime (which counters). We assume that competition always uses resources. We allow an empowered niche to proactively attack the regime when it has gained a sufficient 'potential to influence' (as measured by its institutional capacity). As discussed above, absorption of niches may also be considered as a form of competition. Attacks are not usually fatal immediately. Rather, if successful, an attack results in 'damage' to the attacked sub-system (defined as a reduction in institutional capacity). The regime is allowed a 'counter-attack',

which may erode the niche's institutional capacity (and in turn affect its ability to mount further attacks).

4.3.6 Adaptation: attempt to influence landscape conditions

The regime may attempt to ensure its continued existence by attempting to influence the "rules of the game" (represented in the CF through the landscape). This mechanism might be used, for example, to allow the regime to divert resources into 'lobbying' for increased political influence if it is under stress or perceives a threat. An example might be the case of transport regime actors (e.g., car firms) reinforcing globalisation to lock societies into car dependency (Paterson, 2000).

5 Conclusion

This paper has outlined a CF for analysing and simulating transition dynamics and is broadly consistent with both the available empirical evidence and current theorising about transitions. The CF represents a first step in a research process that is attempting to address the challenge of modelling complex, non-linear societal dynamics in the context of future transitions to sustainability.

In developing the CF, our aim has been to produce a framework that is of immediate practical use in developing simulation models of transition dynamics. The framework should be evaluated in terms of:

- its usefulness as an aid in developing computer simulation models of transitions and, in particular, 'sustainability transitions'
- its fit and consistency both with current theorising about transitions and empirical evidence about transitions.

This is the subject of ongoing work. Our experience so far suggests that the added value lies in the role that it can play in providing a bridge between simulation models, on the one hand, and theory and empirical data, on the other hand.

The CF described in this paper has been used to develop models of specific possible future transitions such as a transition to 'sustainable mobility' in Europe (Whitmarsh and Nykvist, 2008; Whitmarsh et al., 2006; Bergman, et al., 2007). In this example, the transition model describes the current European mobility regime, the associated background socio-technical landscape, and a set of socio-technical niches (representing novel emerging technologies and/or novel lifestyles/social practices). The model is calibrated using quantitative data for the European transport system and can then be used to explore the conditions under which a transition in the mobility system may occur (or not).

Transition models developed using this novel approach can be compared with conventional modelling tools to evaluate the potential for added value in the context of analysing and supporting 'sustainability transitions'.

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