A System Dynamics Model of Socio-technical Regime Transitions

Abstract

Formal modelling of sociotechnical studies has so far focused either on reproducing known historical case studies or on generic transition models that encompass some of the characteristics of the underlying processes. This article presents a model that captures the unfolding dynamics of an existing technological regime and the emerging niches as they compete and respond to landscape pressures. The theoretical basis is the "Multi-Level Perspective" (MLP) framework. The development of new technologies in niches is endogenous and stochastic. Model analysis can be seen as a test of the dynamic consistency of the MLP substitution pathway. Simulation results are consistent with what MLP theory suggests and raise relevant questions and insights with regard to future modelling work on transition pathways and theory development.

Keywords: formal modelling, system dynamics, transition mechanisms, transition pathways.

1. Introduction

Research on sociotechnical transitions and system innovations can offer insight about the factors that enable or inhibit widespread adoption of environmentally sustainable or energy efficient technologies. One influential framework developed in this context is the Multi Level Perspective (MLP) (Geels and Schot, 2007; Geels, 2004; Rip and Kemp, 1998). It has formed the basis for various case studies on sociotechnical transitions (Geels, 2002; 2005; 2006a; 2006b; 2007a; 2007b; Raven 2004; Verbong and Geels, 2007; Van den Vleuten and Raven, 2006; Raven, 2007). However, relatively few modelling studies following the MLP have shed light on transitions so far (e.g., Yucel and Mesa 2008; Kohler et al., 2009; Yucel and van Daalen, 2008). For a broader overview of transition models see Holz (2011), Safarzynska et al., (2011), Safarzynska and van den Bergh (2010) and a special issue on computational and mathematical approaches to societal transitions (Timmermans and de Haan, 2008).

Since the MLP has not received analysis with a formal model there is no assessment of whether the necessary causal factors it postulates are sufficient in order to generate the typical transition dynamics as described in its typology. The construction of a formal model based on a theoretical framework that is derived from concrete cases will make its assumptions credible and allow for an exploration of their implications. This could result in improvements in the theory so as to assure strong internal validity (Davies et al., 2007). Consequently, the work presented in this paper may be of interest to the community of researchers using the MLP, even when they are not using formal models themselves.

The modelling approach used is system dynamics. This choice is motivated by the fact that sociotechnical transitions theories, notably MLP, involve multiple and interacting dynamic processes, time delays, and non-linear effects, such as feedback loops and thresholds. System dynamics is suitable for understanding the behaviour of dynamic systems that exhibit these characteristics (Sterman, 2000).

The emphasis of this study is on evaluating how well the model portrays a particular MLP transition pathway, namely regime substitution, by making explicit the links between the functioning of the regime's social groups and the timing of changes that unfold in a complete substitution process. While these are described in theory and in transition cases, the model enables simulating the forces and the actors in the system and tracing the consequences of their actions over time. In this way, it is possible to test, at least in part, the assumptions under which a substitution pathway can actually take place and whether modelling results are consistent with qualitative descriptions from MLP theory.

The choice of the substitution pathway was based on three considerations. First, developing a model of a specific MLP pathway rather than a generic MLP model may be regarded as a logical and prudent first step. Prior attempts to develop a generic model of the MLP (Bergman et al., 2008) were successful to some extent, but the modellers admitted that they had to reconfigure the model each time in order to reproduce all transition pathways, meaning that they did not really achieve an entirely generic MLP model. In view of this, it was decided that model development in this paper should focus on a single transition pathway. This could result in a consistent, in-depth modelling study of an important pathway. Moreover, it might ultimately contribute to a broader perspective on MLP and allow for identifying essential differences between transition types, that is, once models of other transition pathways would have been developed. In other words, this study is part of a larger, ambitious research line.

A second consideration for choosing the substitution pathway was that it could be broadly conceptualised and understood in terms of feedback loops and a discontinuity between the old and new sociotechnical regimes, and the niche. This could then be modelled following the approach of system dynamics, namely as shifting feedback loops. The de-alignment/re-alignment pathway was considered but not chosen, despite the fact that it involves similar feedback, because it would involve anticipation of de-alignment/re-alignment processes in all of the regime's elements. This would imply a much more complex model.

A final consideration was that the substitution pathway was expected to allow for clear interpretations of model results. This would help to validate the model.

The remainder of the paper is structured as follows. Section 2 offers a brief overview of the Multi Level Perspective (MLP). Section 3 discusses how the substitution pathway dynamics were implemented in the model. Section 4 presents the validation tests with the model and develops the scenarios that were simulated. Section 5 presents the results of numerical simulations. Section 6 concludes.

2. The MLP Framework and Transition Pathways

The Multi Level Perspective (MLP) is a framework for studying (radical) technological change and diffusion. It emphasizes the role of social (group or network) interconnections and dynamics in system change and inertia. System developments are conceptualised as taking place at three levels that include the elements necessary for fulfilling a societal need. They are the outcome of the activities of actors who are embedded in interdependent social groups each with their own set of rules (Geels, 2004). It follows that intergroup coordination and alignment of activities is important. This coordination takes place on a meta-level of the sociotechnical regime. This is a broadened version of Nelson and Winter's (1982) technological regime, that apart from shared engineering and cognitive rules includes scientists, policy makers, users and special-interest groups (Geels and Schot, 2007). Consequently the stability and change of a sociotechnical system is the result of these interactions between multiple social groups. Tensions and mis-matches among activities of different groups can lead to misalignment of rules and create space for change.

The relationship between the three levels of the MLP is conceptualised as follows (Geels, 2002): (i) the landscape at the macro level, which forms the exogenous environment, and through its influence on the sociotechnical regime, it makes certain developments in it easier than others, (ii) the established sociotechnical regime level where incremental technological developments take place that constitute the trajectory of the regime, and (iii) the niche level where radical innovations incubate and proliferate. According to Geels (2004) a socio-technical regime comprises three interrelated elements: (i) a network of actors and social groups, (ii) formal, cognitive, and normative rules that guide the activities of actors, and (iii) material and technical elements, such as artefacts and infrastructures.

Actors and groups influence the trajectory of technology development by adhering to a set of rules that guide their activities. Consequently, the progression of a sociotechnical regime is quasi-(co)evolutionary as many engineers in the production part of the system anticipate, in different ways, the changing needs of many users and the wider selection environment. This reciprocal interaction guides the search heuristics of engineers, rendering them in effect blind to developments outside their focus (Nelson and Winter, 1982), to regulations and standards (Unruh, 2000), to socio-cultural adaptation to technical systems, to sunk investments in machines and infrastructures, and to competencies (Christensen, 1997).

Hence, the stability of the sociotechnical regime influences, but also stems from, technological trajectories. This is part of the reason for the resistance that innovations from niches face in breaking through. They can overcome such resistance if the regime is destabilised, either internally or through landscape pressure, by taking advantage of ensuing "windows of opportunity".

The regime's response to destabilization can be such as to accommodate the landscape pressures and absorb the innovations developed in niches. If this is not possible, it can, under certain conditions, cause a transition to a new regime. In this case, the dynamics and pace of the transition are modulated by the selection environment in which the system exists. In general, this consists of the group of consumers and the institutional framework which includes a regulative, a cognitive and a normative component (Scott, 2008). In the MLP transition typology there are four transition pathways and each one is characterised in terms of the nature and timing of the interactions among the landscape, regime and niche levels (Geels and Schot, 2007).

Landscape pressures and regime dynamics can modulate niche development by creating windows of opportunity, and eventually contribute to niche success or failure. Whether a niche is sufficiently developed in order to become a candidate for an alternative to the incumbent regime is a matter of qualitative assessment based on four criteria (Geels and Schot, 2007): (i) the emergence of a dominant design, (ii) the enlargement of the network of actors, (iii) improvements in the price/performance ratio, and (iv) a cumulative market share of more than 5% for the new technology. Finally, a transition ends when a new socio-technical regime has emerged, meaning that the social and technical aspects of innovations and their use become embedded in the institutional, the production and the user subsystems of the sociotechnical system.

3. Modelling the Substitution Pathway

The model focuses on the substitution pathway and the necessary and the causal mechanisms necessary for reproducing a complete substitution. Hence, it is assumed a priori that the regime lacks the endogenous capacity to respond to the contingency of pressures and persistent problems it faces. The model illustrates the interplay between endogenous feedback processes and contextual, situational factors that determine the dynamics of a substitution transition. Initially the regime is in the reproduction pathway, then it goes through substitution and finally returns to reproduction. It should be noted that there are no case studies of sequential transitions of the same system and consequently such a possibility has not been considered here or in any of the models so far.

Geels and Schot (2007) describe the conditions under which a technological substitution can take place. For this to happen, there has to be some form of significant landscape pressure and at the same time innovations in niches have to be sufficiently developed. Pressures on the regime destabilise it, create misalignment of actor activities and open windows of opportunity for niche innovations to break through.

However, even when niche innovations succeed in entering the market, they can still face resistance from regime actors who invest in improvements of the incumbent technology. Market competition and power struggles influence the eventual outcome of the interaction between incumbents and outsiders. If the innovation replaces the old technology, this has wider consequences, and influences the entire system (see the case in Geels, 2002).

The following sections outline the assumptions and choices that were made in creating the model representation of the sociotechnical regime, the niche, their interaction and the way a transition unfolds.

3.1 The Regime

In order to simplify the modelling task, certain assumptions concerning the level of detail of the model have been made. Figure 1 shows the main elements of the model which includes social groups, and the resources they utilize in order to perform their function and in doing so reproduce the sociotechnical regime. Thus it is a combination of Figures 1 and 2 in Geels (2004). For example, the element of users/consumers is taken to represent the regime of markets and user preferences. Industry production attributes includes the technical characteristics of the technology utilised such as efficiency, price and scale of production. Figure 1 is a high level representation of the model, and is meant to convey the core logic, which is that agents utilise resources in order to supply a function. The complete model includes both a production and a user side and its structure is related to all of the relevant actors detailed in Geels (2004), both for the old and new sociotechnical regimes. The policy making apparatus is taken to represent the public authorities, ministries and executive branches that are involved in governance.

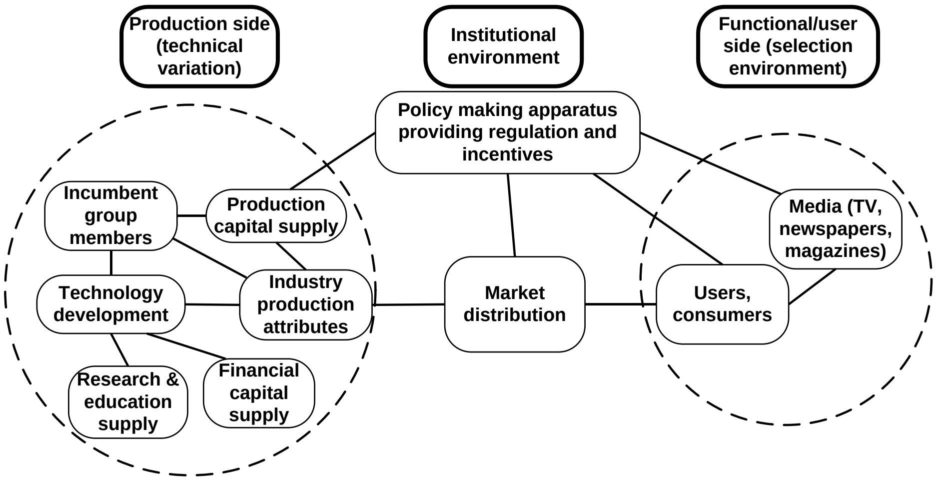

Figure 1. Social groups and resources involved in regime reproduction, as applied in the model.

The links between the model elements are bidirectional and represent the interactions that take place and generate the dynamics of the system. These links are maintained and reproduced as long as there is alignment and coordination of activities in the system. Figure 2 shows the general dynamic logic that the sociotechnical regime follows. Arrows show how one process drives another. For example, the activities of the social groups create an environmental effect at the landscape level. It increases cumulatively and along with other landscape pressures generates problems that are perceived as persistent. They inevitably lead to a search for a new sociotechnical trajectory, a process that generates an adaptive response from the regime by realigning some of the internal processes and activities. The alignment of activities stems from networks of actors and resources, capable of altering both the sociotechnical regime alignment and the niche dynamics. The regime response process involves both inertia and system resistance. Inertia comes in the form of infrastructure being already in place and system resistance is described by *Incumbent resistance* (variable names in *italics*). This represents the unwillingness of *Old regime members* to contribute to, and their active opposition to policies aiming to bring about, change. Broadly, the model logic is that of a stimulus-adaptive system response relationship. In the substitution pathway the inability of the regime to generate an adequate adaptive response results in its eventual replacement. This process has been modelled with distinct model subsystems for the old and new sociotechnical regimes and the niche.

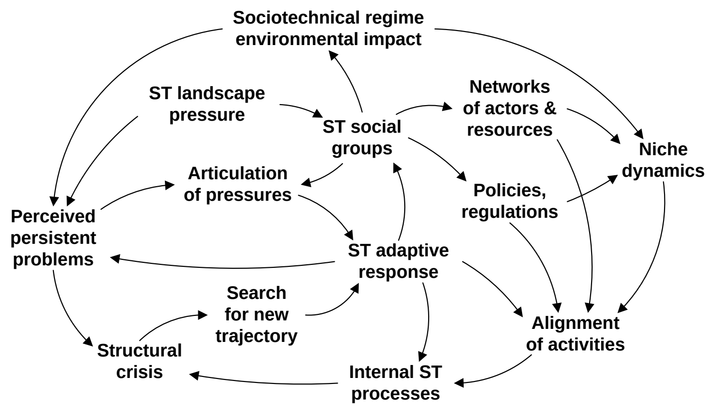

Figure 2. High level representation of the sociotechnical regime

3.2 Niches

The niche part of the model is based on the idea that technological niches and sociotechnical regimes are similar kinds of structures, although different in size and stability (Geels and Schot, 2007). Consequently, the niche module includes variables for *Niche Users* and *Niche Production Capacity*, *Niche R&D*, *Technology Expectations* and *Regulation - Incentives* that contribute to protecting the niche (technological or market) but no variables for established rules or alignment of activities. As a sociotechnical regime consists of a range of technology niches, evaluation of alternative technologies is necessary. This is based on *Technology Performance* and *Technology Price* that comes down with *Cumulative Production*. Figure 3 offers an aggregate conceptual view of how the internal niche dynamics have been implemented in the model. As regime users become gradually aware of the regime's effect on the environment, the need for a new technology arises. This leads to competitive allocation of financial capital (*FC Capital*) to candidate technologies based on *Technology Expectations Fulfilment*.

Technological niches are protected by actors willing to invest time and money in them. It is assumed that government involvement is high in the initial stages, until an internal self sustained flow of capital is established. Niche processes become self-sustaining gradually as production capacity and revenue for each technology increase. The flow of capital into the niche does not cease, however, reflecting its protective character. The reason why actors are assumed to protect non-competitive innovations is the perceived importance of realizing societal and collective aims (Schot and Geels, 2007), which in the context of the model are related to societal issues (conservation, efficiency and sustainability), and expectations that the innovation will become viable in the future. Thus the work on niches is guided by an expectation of future improvement of technological performance and perceived threats caused by environmental degradation or market opportunities. It is through processes of incremental change within each niche and competition between them that a candidate new sociotechnical regime emerges.

Learning about new technologies in the niche takes place with *Cumulative Production* and this can alter the eventual outcome of the technological competition in the niche, as technology performance improvement through *R&D* is stochastic. This is done in order to represent the intrinsic path-dependent nature of technology *R&D* (Arthur, 1989) but also the lack of clear and stable rules to guide the search heuristics of engineers (Schot and Geels, 2007).

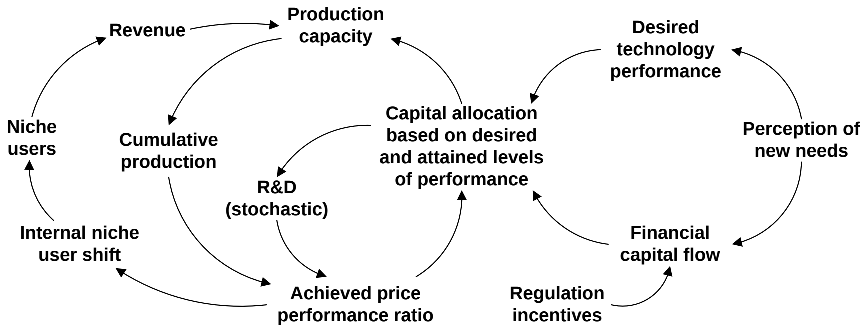

Figure 3. High level representation of the niche

The four criteria for the viability of a niche are included in the model. Consequently, once a technology becomes dominant and exceeds the 5% market share threshold proposed in Geels and Schot (2007), then a percentage of the technology and related level of performance (0-100%) can be transferred to the regime (see Figure 4 below). This reflects the fact that further constraints in the regime might not make possible the full exploitation of technologies developed in niches. An example from the automobile regime is the partial transfer of race car (e.g., Formula 1) technology to every day use. Racing acts as an incubation space out of which certain applications arise, such as Continuously Variable Transmission systems (CVT), which then are transferred and used in commercial cars.

3.3 Niche-Regime Interaction

Figure 4 displays the interaction between the ST regime and niche. *New Regime Science* develops as a result of observing the socially undesirable effects of the regime and is utilised in R&D in the niche. The *Perception of New Needs* and the *Perception of Regime Effect*, drive the *Desired Technology Performance* levels of the niche technologies. The latter is assumed to drive the *Awareness Shift* of the *Old Regime Aware Users* some of which eventually enter the niche. *Regulation - Incentives* is used to create the protected technology space in which the new innovations can flourish. This is done in two ways. First, it is used to enhance the price performance ratio of niche technologies, and second to induce users into the niche and stimulate funding of R&D activities. The W*indow of Opportunity*, influenced by *Political Pressure* from the users who are aware of the regime's environmental impact and their new needs, further stimulates them to move into the niche. I have chosen to represent the drivers of R&D in the niche as *Financial Capital* (which in turn is a function of perceived new needs), *Regulation - Incentives* and *New Regime Science* that is developed as a result of the *Regime's Environmental Impact*.

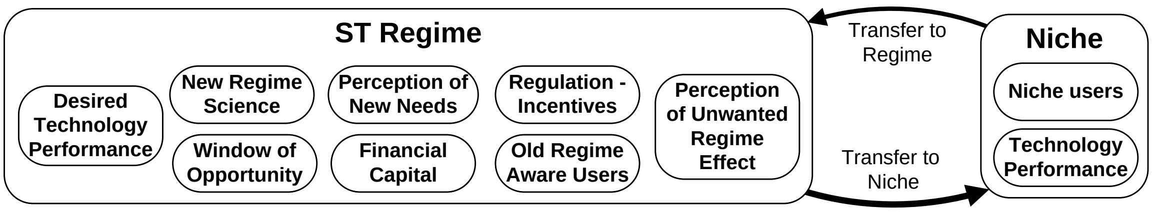

Figure 4. Sociotechnical regime - niche interaction

Old Regime Aware Users are the ones that have become aware of the *Regime's Environmental Impact* and enter niches. It is assumed that the value system upon which they evaluate technology changes. Subsequently, niche users grow in number, choose between alternative technologies, and set in motion processes of niche accumulation that eventually enhance the competitiveness of the innovations and bring about a shift of the remaining *Old Regime Aware Users* to *New Regime Users* (Figure 5). The *Technology Performance* of candidate innovations developed in the niches is transferred in whole or in part in the new regime as the transition is completed (the percentage of transfer can be set prior to running a simulation). Figure 5 illustrates the transition that takes place in the users/consumers group of the sociotechnical regime (see Figure 1). Thus, users choose twice, first on the basis of values prior to entering a niche and then on the basis of technology performance.

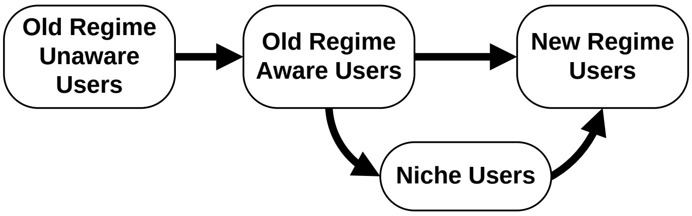

Figure 5. Schematic representation of user transition in the model

3.4 Alignment of Activities

Alignment is an important concept in the MLP as it influences the stability of the regime. Pressures that act on the regime reduce the alignment among the activities of its social groups. Alignment can also decrease as new groups associated with the new regime become active. As the transition is completed it is eventually restored to its original value. The generic way in which the alignment between groups and activities has been conceptualised is shown in Figure 6. For example, group 1 may be associated with production activities of the incumbent regime and group 2 with those of the candidate niche. Assuming that the activities of the niche (A_n) are competitive to that of the regime (A_r), the degree of alignment is calculated as $\max(A_n, A_r)/(A_n+A_r)$.

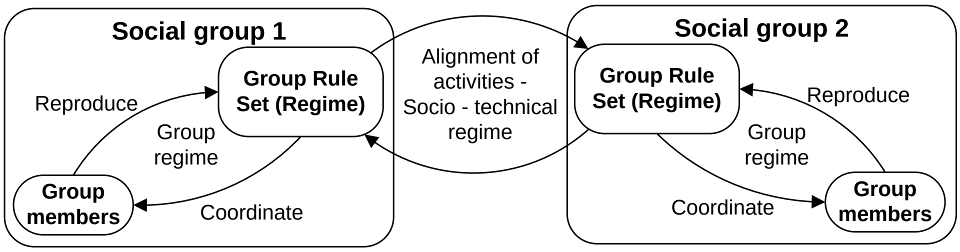

Figure 6. Alignment of activities in the regime

The overall regime alignment is taken to be the average of the *Production Capacity Alignment*, *Production Capital Alignment*, *Rule System Alignment*, *Regime Member Alignment* and *Production Resources Alignment*. It is also depends on the *Window of Opportunity* created by landscape pressures that drive the public perception of new needs and political pressure for change. It is assumed that at least some regime actors perceive this window as an opportunity to deviate from established practices and steer their activities accordingly. Finally it depends on science (*Science Alignment*). If the environmental effect of the incumbent regime is perceived as unwanted then this is due partly to the way scientific activity is pursued and applied, and how its results are disseminated.

4. Validation and Testing

The case studies of socio-technical transitions available in the literature offer limited numerical data The available data are primarily qualitative, historical and anecdotal. In the light of this, the parameter values used in the model reflect stylized facts or are conjectural. However, as the focus is on pattern reproduction and not on reproducing a specific case study, the results are of value particularly in illustrating how delays in processes of the system influence its behaviour.

Sensitivity tests have been performed, both on the delay constants and the equations used in variables.. Large variations in initial conditions and/or variables cause the model's behaviour to vary. However the qualitative behaviour of the model does not change and , the pattern of behaviour the model exhibits is maintained (see results section). This provides evidence for validity of model behaviour and its results which will be reported in the next section. Thus the significant uncertainty surrounding numerical values does not constrain the use of the model as a theory testing tool (Sterman and Wittenberg, 1999).

Due to model size (491 variables, 275 equations), a full presentation of the sensitivity tests that have been conducted would require considerable space which is not available here. Instead, three scenarios were formulated by varying the regime's impact and the delays of the system. Values have been assigned to constants in such a way that the best case scenario represents a situation characterized by a small regime impact and the delays in the system are small. The worst case represents a situation with a large regime effect and long delays. Keeping the pattern of stochastic R&D processes identical allowed for isolating the effect of delays in the system. Testing for these scenarios was expected to result for the best case scenario in an early transition and for the worse case scenario in a delayed transition relative to the reference simulation. The scenario set-up is shown in Table 1 below.

Table 1. Scenarios and constants.

Constant	Reference	Best case	Worst case
Initial old regime environmental effect (unitless)	2000	1000	3000
Window of opportunity open delay	10 years	5 years	15 years
Time to develop production capacity	10 years	5 years	15 years
Delay in regulation effects	15 years	5 years	15 years
Delay in user transition	5 years	2 years	7 years
Regime effect perception delay time	40 years	30 years	50 years
Political pressure change delay time	5 years	2 years	7 years
Time for production capacity depreciation	10 years	10 years	10 years
Time to train in current paradigm	5 years	5 years	5 years
Efficiency improvement delay	3 years	2 years	4 years
Delay in environmental impact	20 years	10 years	30 years
Need perception delay time	10 years	5 years	15 years
Time to train in new paradigm	5 years	3 years	6 years
Time to retrain in new paradigm	10 years	7 years	15 years
Observational delay of regime effect	5 years	5 years	10 years

Further tests were carried out in order to identify conditions under which a complete transition will not take place. The following table presents a list of tests carried out with the model in order to assess the model's behavioural validity. For example, testing with a zero initial environmental effect results in a delayed transition and testing with no effect results in no transition, as expected.

Table 2. Behaviour tests carried out with the model

Test	Behaviour
Zero initial regime environmental effect	Delayed transition
Zero initial regime environmental effect & zero regime environmental effect rate	No transition
Zero user perception of the regime's environmental effect	No transition
No political pressure for changes	No transition
No scientific observation of regime environmental effect	No transition because there is no awareness shift.
No regulation, no incentives for development of alternative technologies	Users awareness transition
No change in rule alignment & stability	Users become aware of regime environmental effect
No regime membership change	No transition
No entrance of new members to the regime	Complete transition
Niche technologies of equal development potential (see Figure 12)	Delayed process of transition

5. Results of Model Simulations

Here the results of the simulations are presented. While there are numerous variables of interest in the model, the focus is on those which correspond most closely with the theoretical concepts of the MLP. Figures 7 – 13 illustrate the behaviour of model variables over time (horizontal axis in years) for the reference, best and worst case scenarios.

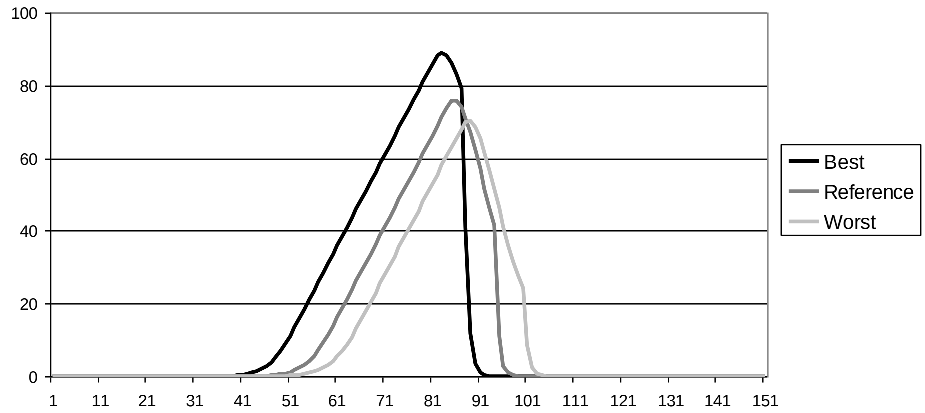

Figure 7. Users of niche technologies over time

In the best case scenario, the niche starts developing approximately 15 years earlier and peaks higher at 9% of the total users of the system (note: y axis in figure 7 is 0 – 100 users for illustration purposes while total system users is 1000). What is of interest is the relative magnitude and timing between the scenarios. It is worth noting that one of the conditions for the viability of the niche postulated by Geels and Schot (2007) is that niche users make up about 5% of the total market share, a threshold which is consistently exceeded in all three scenarios.

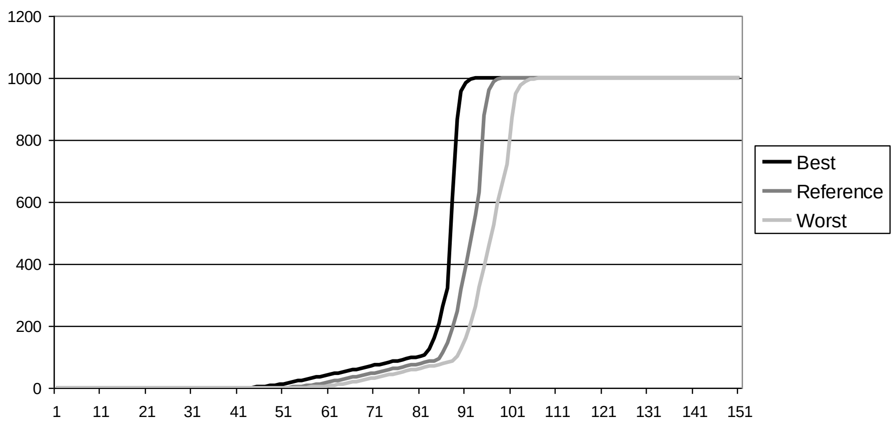

Figure 8. Total new regime users plot

In the best scenario the system undergoes a transition about twenty years earlier than in the latter case (Figure 8). In all three scenarios the general pattern of technology adoption among users is similar despite the fact that delays in the worst case scenario are double that of the best case scenario (see table 1). In effect, changing the delays does not change the way the dominant loops operate in the model. As expected, the production capacity behaviour follows the trends of the users closely (Figures 9, 10, 11, 12).

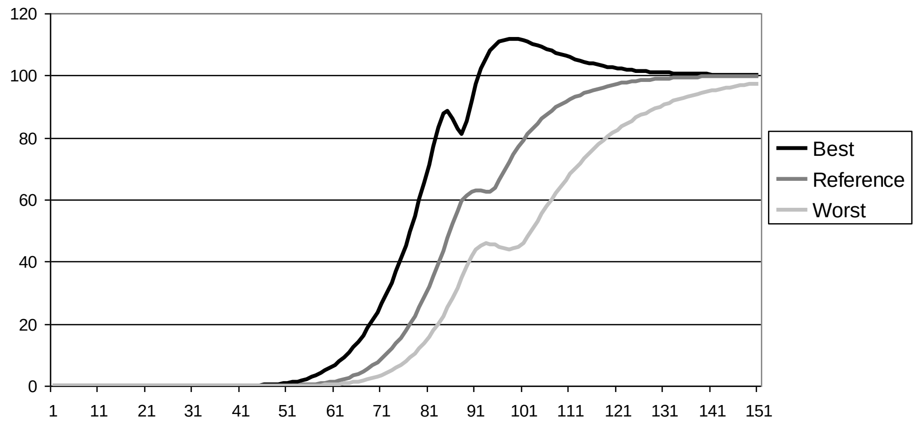

Figure 9. Total new regime production capacity plot

The total new capacity in the model (y axis in Figure 9) is the sum of the capacity in all three candidate niches (Figure 10) and the new regime (Figure 12). The difference in behaviour is observed because in the best case scenario, the delays in the system allow capacity to build up quickly before capacity in the niches, which peaks in years 82-92, depreciates. Furthermore, in the best case scenarios capacity exceeds 100, which is the required capacity for supplying the user population demand. An explanation for this is that competition among the technologies in niches builds capacity which eventually is removed, with some delay, when users move to the new regime. This is what creates some temporary overcapacity in the system. This is a phenomenon that has been documented in transition studies (Verbong and Geels, 2007) and is also present in the history of electronics and micro chips (Brown and Linden, 2009).

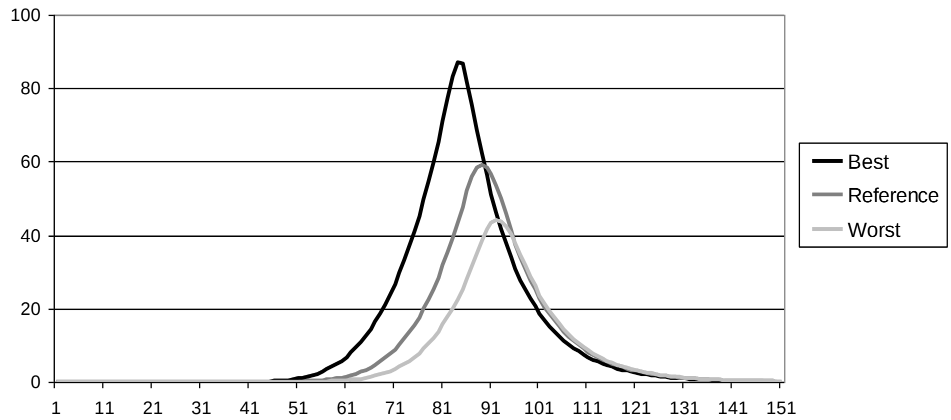

Figure 10. Total niche production capacity

The total capacity in the system (old and new regime and niches) available at any moment to supply user needs is shown in Figure 11. The difference is that in the best scenario the system does not enter a state of under-capacity as the system responds quickly and builds new capacity. In the worst scenario the system experiences the most severe under capacity. This can be explained by looking at Figure 12 which shows the production capacity of the new and old regimes. This behaviour holds in general for any damped control system. All other things being equal, the more rapid the response to a stimulus is, the less time it takes to come to rest. Note that while capacity starts to increase earlier in the best case, the system comes to equilibrium at approximately the same time under the reference scenario.

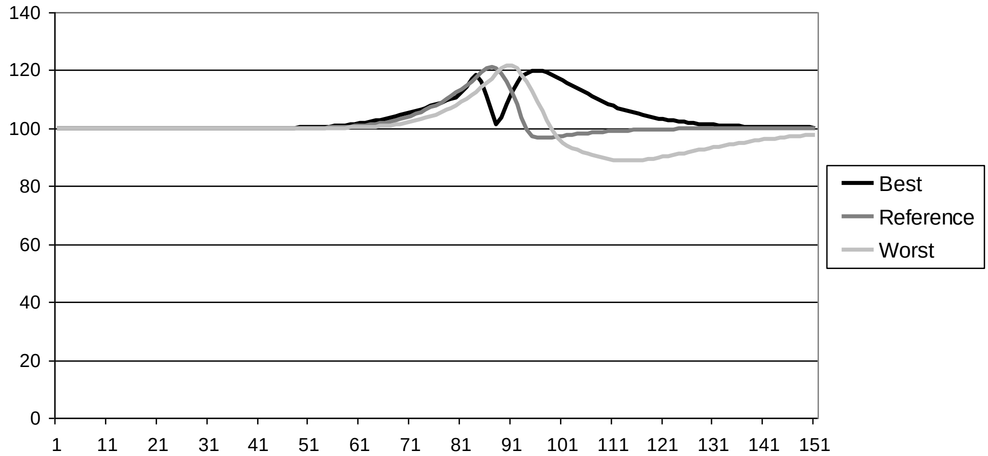

Figure 11. Total system capacity plot (old, new regime & niche)

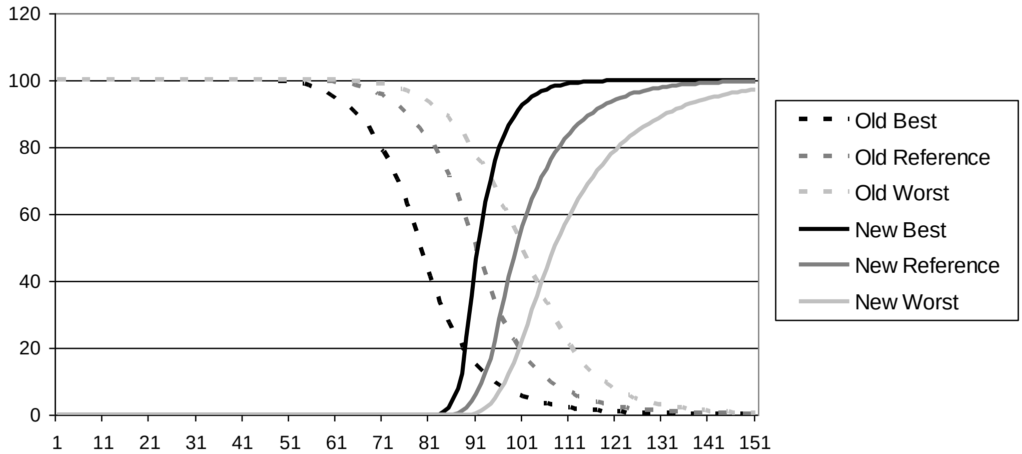

Figure 12. Regime capacity transition

Figure 13 shows a what-if scenario where the model is set to reference scenario but with the added complication that technologies developing in the niches have the same development potential, resulting in no clear substitute to emerge. Because of the increased uncertainty, actors hesitate to commit to niche alternatives and technology development is delayed. The behaviour illustrated in Figure 13 is logical in this sense as this is a typical mechanism (although not the only one)[1] in systems undergoing a transition. It shows the possibility of delay in system transition if competition between innovations is prolonged or if more than one innovation is adopted.

[1] I would like to thank one of the reviewers for pointing this out.

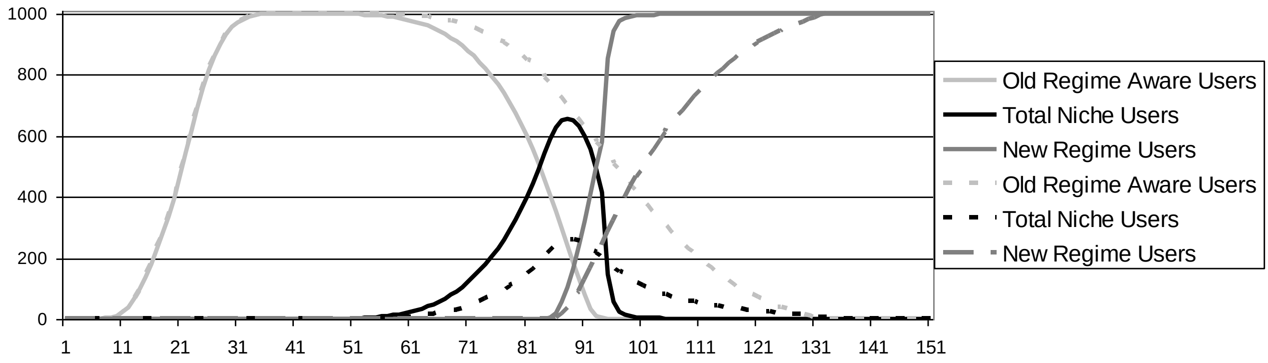

Figure 13. Comparison of user transitions between the reference and equipotential niche technologies scenarios

As this model was not based on a concrete historical case study against which it can be validated, deriving as much output as possible from the model was desirable for two reasons. First, to provide evidence for its validity. Second, as the model is of medium size (491 variables, 275 equations, see Appendix), there are numerous variables that can be plotted with time, each revealing some aspect of the transition process. The framework of Smith et al. (2005, Figure 1) provides another way for visualising a transition process in terms of the locus of resources and the alignment – coordination of activities. They define four transition contexts in terms of which a transition process can be analysed. Model output in Figure 14 shows the trajectory of the simulated reference scenario.

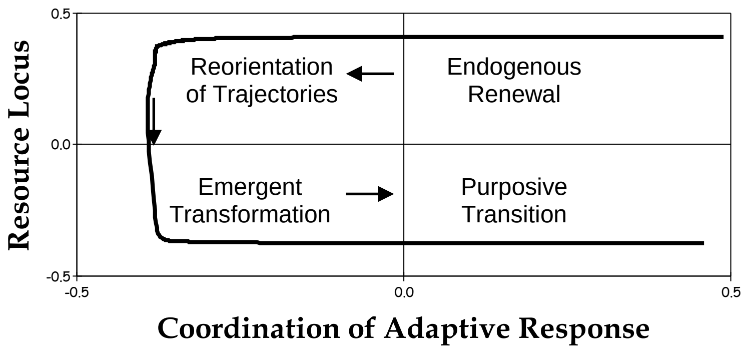

Figure 14. Transition trace in terms of transition framework of Smith et al. (2005)

The trajectory of the model starts on the top right, in the renewal mode and proceeds to reorientation of trajectories, a state in which solutions to the persistent problems are sought within the regime members and resources. However, in the substitution pathway the regime is unable to generate an endogenous response to landscape pressures causing its coordination to break down. In response, technologies that have emerged in niches are assessed in order to arrive at a substitute. Resources and capabilities situated outside the incumbent regime are required to generate a response to the persistent problems the regime faces. Subsequently the trajectory moves to the third quadrant of emergent transformation. The interpretation of this is that the incumbent regime contributes some of its resources to the new regime while the rest is left to depreciate and disappear. At this point there is no way to distinguish the niche that will become dominant since niche R&D is stochastic. Finally as the coordination among the members of the new regime increases the process enters its purposive phase where all of the resources of the new regime and its activities gradually become aligned.

Plotting the time the system spends in each quarter (Figure 15) provides some relevant information for governance. What is required is a swift assessment of whether the regime can endogenously generate an appropriate response to the pressures it is subject to. The aim is to avoid "muddling through" the reorientation of trajectories which takes up considerable time, and instead move quickly to the emergent transformation phase where viable solutions can be found. Figure 16 shows a comparison of the best and worst case scenarios simulated in which the cumulative build up of delays at the end of the transition is illustrated.

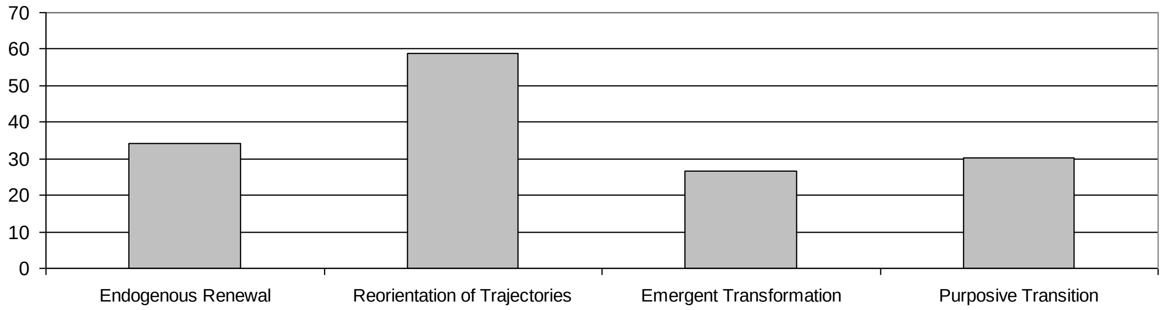

Figure 15. Amount of time the sociotechnical systems spends in each transition contexts

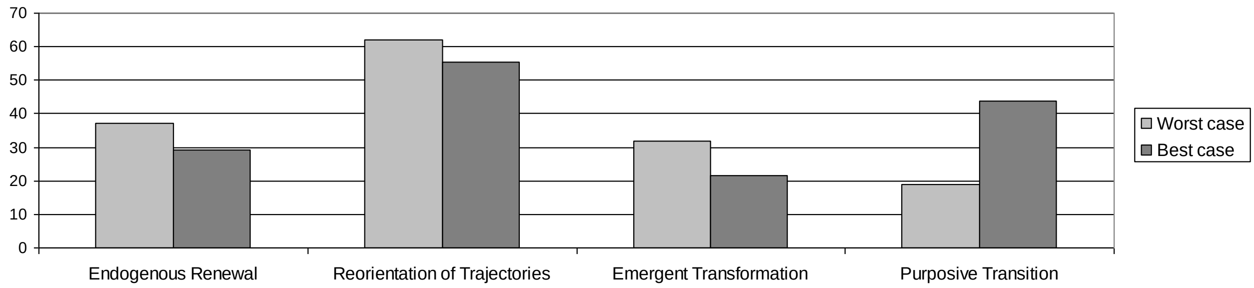

Figure 16. Comparison of the time the system the spends in each transition context in best and worst cases

Looking again at the descriptions of types of transition pathways it is possible to split them in two sets, assuming that the break-up of alignment and coordination of activities of social groups results in the break-up of system organization. The breakdown of organization is used here in the same sense as it is used in autopoiesis theory (Maturana and Varela, 1980) to denote the end of the autopoiesis process that sustains the living organism (in this case the equivalent entity is the sociotechnical system). Hence, the first set includes the reconfiguration and transformation pathways, while the second includes the substitution and de-alignment realignment pathways. In this way an idealized substitution trajectory is shown in Figure 17:

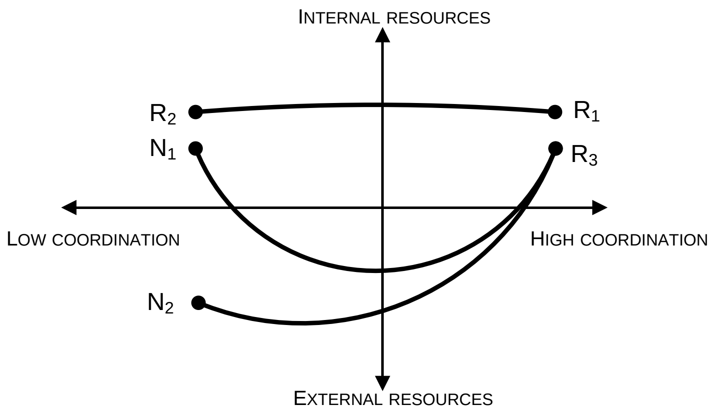

Figure 17. Conceptualized trajectory of the substitution pathway

Here the established sociotechnical regime's trajectory ($R_1 - R_2$) represents the decrease in coordination and eventually the break up of the system's organization. The two trajectories $N_1 - R_3$ and $N_2 - R_3$ represent different possibilities where niches using resources found within the established regime (N_1) or outside of it (N_2), develop into a new regime (R_3) that substitutes the established one (R_1). Consequently solutions can be developed in internal regime niches utilising resources and competencies of outsiders (Van de Poel, 2000) or in external niches outside of the focal regime that eventually come to substitute it. This is an issue that could be looked at in more detail in future modelling studies.

Further output from the model provides food for thought. It was possible to compare model output with Figure 2 in Schot and Geels (2007). This provided a further test of model validity as this particular study was not taken into account during model development and thus allows for an additional validity test. Comparison of the two patterns (Figure 18) is possible because each deals with market niches characterized by some form of cognitive and social isolation, and portray the replacement of the dominant ST regime.

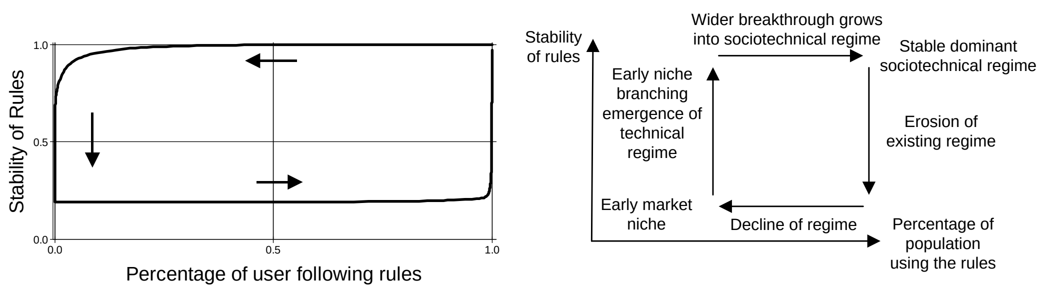

Figure 18. Emergence and breakthrough of regimes: model output (left side) compared with conceptualization by Schot and Geels, (2007, Figure 2)

The horizontal axis in both figures depicts the number of adopters that as a consequence adhere to a different rule set. The similarity of pattern is striking as is the difference of clockwise and anticlockwise trajectories. The two figures offer contrasting views on the same process, namely competition between the new emerging sociotechnical regime and the replacement of the prevailing dominant sociotechnical regime. Model output (left) shows the de-legitimization of rules as diminishing numbers of users adhere to them. Eventually this leads to rule erosion and instability. As the new regime emerges, increasing numbers of users follow the new set of rules, and their stability rises. The postulated figure by Schot and Geels (2007) provides a different progression of events with the erosion of the regime and the diminishing stability of rules preceding the decrease of the number of users. In the light of this, there are three possible explanations. First, that the model is wrong. However, to the extent that the results make sense, this is an unlikely explanation. Second, that the model is right but the choice of variables has produced a figure which is inconsistent with theory. Third, that the theoretical figure does not hold for the technological substitution pathway or does not hold generally. This is a point that requires more work both in terms of modelling and theory in order to arrive at solid conclusions.

6. Conclusions

This paper presented a system dynamics model of the substitution transition pathway of the MLP. It captures the unfolding dynamics of an existing sociotechnical regime and the emerging niches as they compete and respond to landscape pressures. In particular, it represents the dynamics of the substitution pathway. The development of new technologies in niches is endogenous and stochastic. Simulation of the model provided a partial test of the dynamic consistency of the MLP substitution pathway and raised some interesting questions and insights with regard to future modelling work on transition pathways and theory development.

Simulation results are consistent with what MLP theory suggests. Starting from causes and drivers stipulated in theory, the model produces behaviour which is consistent with the theoretical description of the specific pathway. Hence the model provides evidence for the dynamic consistency of the substitution pathway of the MLP. It shows that the behaviour of the substitution pathway as described by the MLP can be produced by the factors it postulates. In a broader sense, it illustrates how formal models can provide a complementary test for theory, even when those theories are stated in entirely qualitative abstract terms, and in a context which does not lend itself easily to explicit dynamic analysis. An unavoidable intermediate step is the choice of parameter values and the interpretation of the simulation results.

With regard to the latter, a methodological insight that this study emphasizes is the trade-off between the breadth of model scope and interpretation of model results. The model represents only the substitution pathway. Compared to the model of Bergman et al. (2008), which reproduces all five transition pathways of the MLP with considerable difficulties involved, there is much less room for interpretation of results because the scope of the model is narrower. In their case, in addition to model set up, structural adjustments were required in order to represent different transitions. For example, this was the case with the transition from horse-drawn carriages to automobiles. Furthermore, in discussing the results of their simulations they noted that their model captures the transition pathways but that distinguishing between the transformation and reconfiguration pathways by looking on the results is a matter of interpretation. A comparison of the model of Bergman et al (2008) with the model presented here, reveals that there is a trade-off between the scope of the model and the room for interpretation of the results. The implication of this is that future modelling attempts on transition pathways could focus on a single transition path at a time. This would then allow for comparison of different models in terms of structural similarities and differences. In this way a coherent body of knowledge can be build about transition pathways and the particular system elements and conditions that induce or inhibit them.

Further insights for future modelling can be derived from the critique of Wittenberg (1992) on Sterman's model of scientific revolutions (1985). This critique was that there is incommensurability between different science paradigms. Extending the argument in cases of complete regime substitution, there is a similar incommensurability, notably of values in a broad sense. The shift in values, belief systems, ideologies and public opinion are at the core of the transition process (Geels, 2010). This is well illustrated, for example, in the hygienic transition (Geels, 2005) and the transition from horse carriages to automobiles (Geels, 2006a). While in the current model study an effort has been made to incorporate this in *Awareness Shift* variable and by disaggregating users in aware and unaware categories, this is a point that should be looked at in more detail in the future. This would also involve dealing with the fact that users and producers of technology often have different priorities and as a result different assessments of technologies.

Finally, model results generate some interesting questions regarding the nature of transitions. Drawing on figures 14 and 17 two questions are worth asking. First, under which circumstances does diminishing regime coordination lead to a break-up of system organization? Is this always the case? Theory so far has looked at how ST regimes are created, transform, and adapt but not at how and when they dissolve. The second question derives from Figure 18. Looking at the evolutionary pattern of stability of rules and users adhering to regime rules, and comparing model output to theory, the question is whether and under which conditions, rule destabilisation precedes the decrease of user numbers or the order is reverse. These questions demonstrate that theory development can benefit from modelling in strengthening its internal validity and experimenting to produce novel theoretical insights.

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Appendix: Model Equations

	Variable Name	Definition
1	Required Niche Capacity	'Total Niche Users'*'User Capacity Conversion Factor'
2	Users outside niches	(1000-'Total Niche Users')/1000
3	Stability of Rules	'Rule system stability'
4	% of users using old regime rules	('Old Regime Unaware Users')/1000
5	Max number of users following new or old rules	MAX('% of users using old regime rules','% of users using new regime rules')
6	Total New Capacity	'New Regime Capacity'+NUMBER('Total Niche Capacity')
7	Total Niche Capacity	ARRSUM(NUMBER('Niche Production Capacity'))
8	Tech Performance Transfer to Regime	ARRSUM('Tech performance to Regime')
9	Tech Performance increase	ARRSUM('Tech Perf Improvement')
10	Total Niche Users Entering New Regime	ARRSUM('Users Entering New Regime')
11	Actual Niche Users	ARRSUM('Niche Users')
12	Resource Transfer from Incumbent Regime	'Shift of Resources Flow'
13	Resources Depreciation	(1-MIN(1,'Required old resources'))* MAX('Regime Resource Usage Flow','Production regime resources'/1<<yr>>)
14	Regime Outside Resources Ratio	'Regime Total Resources Ratio'/'Outside Total Resources Ratio'/10
15	Scope for Regulation Switch	DELAYINF(MIN(1,'Scope for regulation'),1<<yr>>,1,'Scope for regulation')
16	Change scope for regulation	('Political pressure'/MAX(1,('New regime competitiveness'/MAX(1,'Old regime competitiveness')))-'Scope for regulation')/1<<yr>>
17	Total System Capacity	'Total Regime Capacity'+NUMBER(ARRSUM('Niche Production Capacity'))
18	Total Niche Users	'Potential New niche Users'+ARRSUM('Niche Users')+'Recurrent Niche Users'
19	Users Entering New Regime	('Niche Users')*(1-'Niche Market Release') /1<<yr>>
20	Niche R & D Depreciation	'Niche R & D'*(1-'Niche Market Release')/1<<yr>>//'Tech

		performance to Regime'
21	Total New Regime Users	'New Regime Users'+'Dominant Niche Users'
22	Old Regime Production Investment Flow	'Capital Control'[INDEX(2)]
23	Capital Control	PRIORITYALLOC('Old Regime Production Capital'/1<<yr>>,{MAX(0/1<<yr>>,'Investment shift'),'Old regime production investment'},{1,1})
24	Investment Flow	Capital Control'[INDEX(1)]*MIN(1,'Required New Regime Production Investment')
25	Niche PP ratio market threshold	'Niche market threshold'*'Niche dominant tech PP ratio'
26	Niche dominant tech PP ratio	MIN(1,RUNMAX(ARRMAX('Protected Niche Perf Price Ratio'))/'Incumbent Perf Price Ratio')
27	Niche market threshold	MIN(1,RUNMAX('Dominant Niche Users')/(('Total old regime users'+ARRSUM('Niche Users'))*0.05))
28	Knowledge Transfer to Regime	'Niche Cumulative Knowledge'*(1-ROUND('Niche Market Release'))/1<<yr>>*'Switch of knowledge Transfer to regime'
29	Niche knowledge accumulation	(ARRSUM('Niche Rate of Knowledge Accumulation'))/1<<yr>>*ROUND('Niche Market Release')
30	Niche Rate of Knowledge Accumulation	'Technology Performance'/MAX(1,'Niche Tech Learning')
31	Tech performance to Regime	'Technology Performance'/1<<yr>>*(1-'Niche Market Release')*'Switch of tech performance transfer to regime'
32	Tech Learning Rate	'Product Discard'*'Tech R & D'*1<<yr>>
33	Recurrent Users Entering New Regime	('Recurrent Niche Users')*(1-'Niche Market Release')/'Niche Product Use Time'
34	Redistribution of Users With Preference	PRIORITYALLOC('Recurrent Niche Users', ('Recurrent Niche Users'*'User Choice'.'Competitiveness diff'), {'User Choice'.'Competitiveness diff'[INDEX(1)],'User Choice'.'Competitiveness diff'[INDEX(2)],'User Choice'.'Competitiveness diff'[INDEX(3)]})
35	Potential Users Entering New Regime	('Potential New niche Users') *(1-'Niche Market Release')/1<<yr>>
36	Regime effect induced Tech Perf Targets	'Perception of regime effect'^'Perception of new needs'/1<<yr>>
37	Niche Critical Mass Indicator	MIN(1,MAX(IF ('Dominant Niche Users'/'Total old regime users'<'Market niche development threshold',0,1) ,'New Regime Users'))
38	Scaled Niche Tech Capacity	'Niche Production Capacity'/100
39	Required Capacity	MAX(0,'Niche Required Capacity'-'Niche Production Capacity'*1<<yr>>)
40	New Users from Niche	MAX(0,MIN(1,'Old Regime Aware Users'))*'Dominant Niche Users'/1<<yr>>*'Niche Critical Mass Indicator'
41	Niche Market Release	MAX(0,ARRMIN('Niche Protection Review')/MAX(1,'New Regime Development Indicator'))
42	Dominant Niche Users	ARRSUM('Niche Users')+'Recurrent Niche Users'
43	Protected Niche Perf Price Ratio	'Regulation - Incentives'*('Perf Price Ratio')
44	Niche Potential Users	MAX(0,MIN(1,'Old Regime Aware users'/MAX(1,('Regulation - Incentives'-1)*RUNMAX(ARRMAX('Perceived Tech Improvement'))*'Window of Opportunity' * 'Niche Market Release')))*('Regulation - Incentives'-1)* RUNMAX(ARRMAX('Perceived Tech Improvement')) *'Window of Opportunity' * 'Niche Market Release'/1<<yr>>
45	Incumbent Perf Price Ratio	'Old tech efficiency'/'Incumbent Tech Price'
46	Returning Users	Redistribution of Users With Preference'*'Niche Market Release'/1<<yr>>
47	Performance Price Ratio	(('Technology Performance'/MAX(1,ARRMAX('Technology Performance')))/'Tech Price')

48	Tech Price Change	('Unit cost T1'-'Tech Price')/'Price adjustment time'
49	Unit cost	Initial Tech Cost'*MIN('Cumulative Production'^'Tech Cost Exponent',1)
50	OEM Production	Production
51	Niches Expenditure Stream	Revenue/MAX(1/1<<da>>,(MIN('Tech Perf Improvement',Revenue/2<<da>>)+MIN('Tech Prod Cap Build Up'*1<<da>>,Revenue/2<<da>>)))* (MIN('Tech Perf Improvement',Revenue/2<<da>>)+MIN('Tech Prod Cap Build Up'*1<<da>>,Revenue/2<<da>>))/1<<yr>>
52	Niches Revenue Stream	(Sales+'FC Allocation'/1<<yr>>)
53	Product Discard	MAX(0,'Niche Users')/'Niche Product Use Time'
54	New Niche Users	MIN(1,'Potential New niche Users'/MAX(1,('User Choice'.'Competitiveness diff')))*('Niche Market Release')
55	Capacity Depreciation	'Niche Production Capacity'/'Capacity depreciation time'
56	Revenue Coverage for Niche Required Capacity	MAX(0,MIN(1,Revenue/MAX(1,'Required Capacity')))
57	Niche Production Capacity build up	FOR (i=TechRange|MAX(0,'Revenue Coverage for Niche Required Capacity'[INDEX(i)] *DELAYMTR('Required Capacity'[INDEX(i)],'Cap build up delay'[INDEX(i)],1,0)))/1<<yr^2>>
58	Sales	MAX(0,MIN(Inventory,'Niche Users'))/1<<yr>>
59	Niche Production	FOR (i=TechRange|MAX(0/1<<yr>>,MIN('Niche Production Capacity'[INDEX(i)],DELAYMTR('Niche Users'[INDEX(i)],1<<yr>>,1,0)/1<<yr>>)))
60	Technology Expectations Fullfilment	Tech Expectations'/MAX(1,'Desired Technology Performance')
61	Periodic Target Adjustment	NUMBER(PULSE(1,STARTTIME+0<<yr>>,'Target Adjustment Time'))
62	Input Tech Expectations	{PULSE(1,STARTTIME,500<<yr>>), PULSE(1,STARTTIME+'Tech 1 headstart',500<<yr>>)}
63	FC accumulation	Flow of Financial Capital'/1<<yr>>
64	Net Change In Desired Tech Perf	('Technology Performance'-'Desired Technology Performance')/'Goal Adjustment Time'*'Periodic Target Adjustment'
65	FC expenditure	ARRSUM('Tech R & D')
66	Error in Tech Perception	'Technology Performance'-'Perceived Tech Improvement'
67	Perceived Tech Improvement Change	'Error in Tech Perception'/'Perception Adjustment Time'
68	Tech Expect Change	('Perceived Tech Improvement'-'Tech Expectations')
69	Tech Perf Improvement	('Niche R & D'-'Technology Performance')/'Tech Perf Improvement Time'/MAX(1,'Technology Performance') *'New Regime Scientists Ratio' *ROUND('Niche Market Release')
70	Tech R & D	FOR (i=TechRange|('R & D effectiveness'[INDEX(i)]*'FC Allocation'[INDEX(i)]/2)/(MAX(1,'Technology Performance'[INDEX(i)])*1<<yr>>)) *('New Regime Scientists Ratio')*'New theory'
71	FC Allocation	PRIORITYALLOC(MAX(0,('Financial Capital')),MAX(0,'Desired Technology Performance'),MAX(0,'Technology Expectations Fullfilment')*'Perf Price Ratio')*'Niche Market Release'
72	Resource Locus	'Scaled RRes ratio'
73	Coordination of Adaptive Response	'Scaled alignment rules & activities'
74	Normalised Policy WoO	1-'Window of Opportunity'
75	Niche	CEIL(MAX(0,1-'Niche Market Release'))
76	Purposive_Transition	MAX(0,MIN(1,'4th quadrant'))
77	Emergent_Transformation	MIN(1,'3rd quadrant')

78	Reorientation_of_Trajectories	MIN(1,'2d quadrant')
79	Endogenous_Renewal	MIN(1,'1st quadrant')
80	Quadrant 4	FOR (Quadrants='Endogenous Renewal'..'Purposive Transition'|'Transition Quadrants'[INDEX(NUMERICAL(Quadrants))]) *'Array 4'
81	Quadrant 3	FOR (Quadrants='Endogenous Renewal'..'Purposive Transition'|'Transition Quadrants'[INDEX(NUMERICAL(Quadrants))]) *'Array 3'
82	Quadrant 2	FOR (Quadrants='Endogenous Renewal'..'Purposive Transition'|'Transition Quadrants'[INDEX(NUMERICAL(Quadrants))]) *'Array 2'
83	Quadrant 1	FOR (Quadrants='Endogenous Renewal'..'Purposive Transition'|'Transition Quadrants'[INDEX(NUMERICAL(Quadrants))]) *'Array 1'
84	Transition Quadrants	{'1st quadrant','2d quadrant','3rd quadrant','4th quadrant'}
85	Production Capacity Alignment	(MAX('Old Regime Capacity','New Regime Capacity')/SUM('New Regime Capacity','Old Regime Capacity'))
86	Old Aware Total Users Ratio	'Old Regime Aware Users'/'Total members'
87	Membershift Shift Actual	'Old Regime Members Control'[INDEX(2)]*'Switch Membership Shift'
88	Old Regime Members Disappear	'Old Regime Members Control'[INDEX(1)]
89	Old Regime Members Control	PRIORITYALLOC('Old regime members'/1<<yr>>,{'Creative destruction','Membership shift'},{0,0})
90	New Total Production Resources Ratio	'Production resources of the new regime'/('Production regime resources'+'Production resources of the new regime')
91	Niche Perf Price Ratio	RUNMAX(ARRMAX('Perf Price Ratio'))
92	New Regime Technology Expectations Fullfilment	'New tech efficiency'/MAX(1,'New Regime Technology Expectations')
93	New Production Capital from Regulation Incentives	('Regulation - Incentives'-1)*'Regulation Incentives coverage of New Production Capital Needs' *'Required New Regime Production Investment'/1<<yr>>
94	4th quadrant	'Purposive Transition'
95	3rd quadrant	'Emergent Transformation'
96	2d quadrant	'Reorientation of Trajectories'
97	1st quadrant	'Endogenous Renewal'
98	Regulation Incentives coverage of New Production Capital Needs	MIN(1,'Regulation - Incentives'-1/MAX(1,'Required New Regime Production Investment'))*MIN(1,'New regime members')
99	Required New Regime Production Investment	MIN(1,'Regulation - Incentives'-1/MAX(1,'Required New Regime Production Investment'))*MIN(1,'New regime members')
100	Actual User Transition	MAX(0<<yr>>,MIN(1<<yr>>,'Old Regime Aware Users'/MAX(1/1<<yr>>,'User Transition')))*'User Transition'/1<<yr>>
101	Lowering of Barriers	MAX(0,MIN(1,'Barriers to Entry'/('New total production capital ratio'*'Ratio of users against old rules'*'Regulation - Incentives'))) *'New total production capital ratio'*'Ratio of users against old rules'*'Regulation - Incentives'/1<<yr>> *(1-'Alignment of rules & activities')
102	Raising Barriers	MAX(0,(MAX('Regime Total Members Ratio','Outside total members ratio')-'Barriers to Entry'))/1<<yr>>
103	Tech Performance Transfer from Niche	Tech performance to Regime'*'% of Niche Tech Perf to Regime'
104	New Regime Development Indicator	MAX(0,'Competitiveness diff'.'Competitiveness diff'*'New Old users ratio'*'Outside total members ratio')
105	Shift of Resources Flow	'Resource Allocation'[INDEX(1)]

106	Regime Resource Usage Flow	'Resource Allocation'[INDEX(2)]
107	Resource Allocation	PRIORITYALLOC('Production regime resources'/1<<yr>>,{'Shift of resources','Regime Resource Usage'},{1,1})
108	New Old Regime Scientists	'New Regime Scientists'/MAX('Current Regime Scientists',1)
109	Creative destruction	(1-'Barriers to Entry')* MAX(0,MIN(1,ROUND('Old regime members',0.001)/('New regime members'-ROUND('Old regime members',0.001))))* ('New regime members'-ROUND('Old regime members',0.001))/('Time for infrastructure depreciation'*'Regime Total Members Ratio')
110	Total Aware Users	'Total New Regime Users'+'Old Regime Aware Users'
111	Niche Protection Review	MAX(0,MIN(1,'Incumbent Perf Price Ratio'/'Protected Niche Perf Price Ratio'))
112	New Price-Perf Ratio	'New Regime Users'*'New Regime Capacity'/'New tech efficiency'
113	Old Price-Perf Ratio	('Old Regime Unaware Users'+'Old Regime Aware Users')*'Old Regime Capacity'/'Old tech efficiency'
114	Experimental anomalies explained	MIN('Number of experimental anomalies','New theory'/MAX(1,'Number of experimental anomalies')) /1<<yr>>
115	Experimental anomalies	MAX(0/1<<yr>>,'Experimental Observation'*(1-'Confidence in New Regime'))
116	New total production capital ratio	'New Regime Production Capital'/('Old Regime Production Capital'+'New Regime Production Capital')
117	User capacity needs coverage	'Total Regime Capacity' /('Required New Regime Capacity'+'Required old regime capacity')
118	Knowledge generation	('New technical solutions'/MAX(1,'Flow of Financial Capital'))/1<<yr>>
119	Ratio of old regime users against rules	Old Regime Aware Users'/('Old Regime Aware Users'+ROUND('Old Regime Unaware Users'))
120	Formation of new actor network	(MAX(0/1<<yr>>,(1-MIN(1,'Alignment of rules & activities'))*('New technology expectations'/MAX(1,'New tech efficiency'))*MAX(0,'Efficiency differential')*(1-'Barriers to Entry'))*'Switch New Regime Members'*'Regime Outside Resources Ratio'+'Old Regime Members Disappear')*'Ratio of users against old rules'/1<<yr>>
121	New regime evaluation	'Efficiency differential'*'New old users'*'New tech efficiency'/MAX(1,'New Regime Technology Expectations')
122	Resistance build up	MAX((MAX('Regime Total Members Ratio','Outside total members ratio')-'Incumbent resistance'),0)/1<<yr>>
123	Total production investment	'New regime production investment'+'Old regime production investment'
124	Production Resources Alignment	(MAX('Production regime resources','Production resources of the new regime')/ SUM('Production regime resources','Production resources of the new regime'))
125	Scaled alignment rules & activities	'Alignment of rules & activities'-0.5
126	Pursposive Transition Change	IF ('Scaled alignment rules & activities'>0 AND 'Scaled RRes ratio'<0,1,0)/1<<yr>>
127	Emergent Transformation Change	IF ('Scaled alignment rules & activities'<0 AND 'Scaled RRes ratio'<0,1,0)/1<<yr>>
128	Reorientation of Trajectories Change	IF ('Scaled alignment rules & activities'<0 AND 'Scaled RRes ratio'>0,1,0)/1<<yr>>
129	Endogenous renewal Change	IF ('Scaled alignment rules & activities'>0 AND 'Scaled RRes ratio'>0,1,0)/1<<yr>>
130	Alignment of rules & activities	'Alignment of activities'*'Rule System Alignment' //1
131	Scaled rule system alignment	'Rule System Alignment'-0.5
132	Scaled RRes ratio	'Regime Total Resources Ratio'-0.5
133	Scaled alignment of activities	'Alignment of activities'-0.5

134	New tech potential	'New tech efficiency'*'New theory'
135	Effects of New Paradigm on Expectations	New technology expectations'*'New tech potential'*'New Regime Scientists Ratio'
136	New technology	('Effect of outsiders on expectations'*'Effects of new paradigm on expectations' /'Regulation - Incentives')/MAX(1,'New technology expectations')
137	Effect of outsiders on expectations	('Efficiency differential'*'Old Aware Total Users Ratio'+'Flow of Financial Capital'*'New Total Production Resources Ratio'*'Outside total members ratio')
138	Change in new technology expectations	MAX('New technology','New tech efficiency')*'New Technology Expectations Fullfilment'-'New technology expectations')/('Time To adjust expectations')
139	Production Capital Alignment	(MAX('Old Regime Production Capital','New Regime Production Capital')/SUM('Old Regime Production Capital','New Regime Production Capital'))
140	Regime Membership Alignment	(MAX('Old regime members','New regime members')/SUM('Old regime members','New regime members'))
141	Incumbent alignment	(MAX('Incumbent resistance','Incumbent resistance disposed')/SUM('Incumbent resistance','Incumbent resistance disposed'))
142	Science Alignment	(MAX('Confidence in Current Regime','Confidence in New Regime')/SUM('Confidence in Current Regime','Confidence in New Regime'))
143	Needs alignment	(MAX('Perception of current needs','Perception of new needs')/SUM('Perception of current needs','Perception of new needs'))
144	User alignment	(MAX('Old Regime Unaware Users','Old Regime Aware Users','Total New Regime Users') /SUM('Old Regime Unaware Users','Old Regime Aware Users','Total New Regime Users'))
145	Alignment of activities	AVERAGE('Production Capacity Alignment','Regime Membership Alignment', 'Normalised Policy WoO', 'Production Capital Alignment', 'Rule System Alignment','Science Alignment', 'Incumbent alignment', 'Production Resources Alignment') *'Switch Alignment of Activities' +(1-'Switch Alignment of Activities')
146	Old new capacity ratio	'Old Regime Capacity'/('New Regime Capacity'+'Old Regime Capacity')
147	Total resources inflow	('Resources supply'+'Shift of resources'+'Shift of resources') /MAX(1/1<<yr>>,'Resource Usage')
148	Total capital inflow	'Investment shift'+'New regime production capital inflow'
149	Total capital	'New Regime Production Capital'+'Old Regime Production Capital'+'Flow of Financial Capital'
150	Regulation - Incentives effect on new tech efficiency	MAX(1,'Regulation - Incentives'/EXP('New tech efficiency'))
151	Total resource	'Production regime resources'+'Production resources of the new regime'
152	New Regime Scientists Ratio	'New Regime Scientists'/'Total scientists'
153	Current Regime Scientists Ratio	'Current Regime Scientists'/'Total scientists'
154	Required old resources	Required old regime capacity'
155	Old regime resource shortage	MAX(0,'Required old resources'-'Production regime resources')
156	New regime effect	('Total New Regime Users')/MAX(1,'New tech efficiency')*'New Old users ratio'/1<<yr>>
157	Total old regime users	'Old Regime Aware Users'+'Old Regime Unaware Users'
158	New regime resource shortage	MAX(0,'Required new resources'-'Production resources of the new regime')

159	Required new resources	Required New Regime Capacity'
160	Awareness Shift	Perception of regime effect'*'Confidence in New Regime'/1<<yr>> *ROUND('Old Regime Unaware Users',0.001) /('Old Regime Unaware Users'+'Old Regime Aware Users')
161	Old regime sufficiency	'Old Regime Capacity'/MAX(1,'Old Regime Aware Users')*10
162	Required new regime capacity investment	ROUND('Required New Regime Capacity'-'New Regime Capacity',0.1)
163	Old capital capacity ratio	MAX(0,MIN(1,'Old Regime Production Capital'/MAX(1,'Old Regime Capacity')))
164	% resources outside the regime	'Production resources of the new regime'/('Production regime resources'+'Production resources of the new regime')
165	Required old regime capacity	('Old Regime Unaware Users'+'Old Regime Aware Users') *'User Capacity Conversion Factor'
166	Outside Total Resources Ratio	'Production resources of the new regime'/('Production regime resources'+'Production resources of the new regime')
167	Regime Total Resources Ratio	('Production regime resources'+'Resources Transferred from Incumbent Regime')/('Production regime resources'+'Production resources of the new regime')
168	New Capital Sufficiency for Capacity investment	MIN(1,('New Regime Production Capital'+'Regulation - Incentives')/MAX(1,'Required new regime capacity investment'))
169	New Regime Capacity Shortage	MIN('New Regime Capacity'/MAX(1,'Required New Regime Capacity'),1)
170	Required New Regime Capacity	ROUND('New Regime Users',0.1)*'User Capacity Conversion Factor'
171	New regime production investment	MAX('New capacity increase'*MAX(MIN(1,'New Regime Production Capital'),0),(1-MIN(1,ROUND(NUMBER('New capacity increase'),0.1)))*'New Regime Production Capital'/'Time for infrastructure depreciation')
172	New regime production capital inflow	New Production Capital from Regulation Incentives'+'New regime production investment'*MIN(1,'New regime members')
173	Old regime production investment	MAX('Old Regime Capacity'/'Time for infrastructure depreciation'*MAX(MIN(1,'Old Regime Production Capital'),0),'Old Regime Production Capital'/'Time for infrastructure depreciation')
174	Old regime production capital inflow	ROUND(MIN('Old regime production investment',MAX('Regime Total Members Ratio'*('Old Regime Aware Users'+'Old regime members'),0)/1<<yr>>),0.001/1<<yr>>)
175	Total investment	'New Regime Production Capital'+'Old Regime Production Capital'
176	Total Regime Capacity	'New Regime Capacity'+'Old Regime Capacity'
177	Compound efficiency differential	'Resource diff'^'Efficiency differential'
178	Ratio of users against old rules	ROUND(('Old Regime Aware Users'+'New Regime Users'+'Total Niche Users')/('Old Regime Unaware Users'+'Old Regime Aware Users'+'Total New Regime Users'+'Total Niche Users'),0.0001)
179	Resource differential	ABS('Production resources of the new regime'/('Production resources of the new regime'+'Production regime resources'))
180	Regime Total Members Ratio	'Old regime members'/('Old regime members'+'New regime members')
181	Outside total members ratio	MIN(1,'New regime members'/('Old regime members'+'New regime members'))
182	Old New users ratio	MAX(0,'Old Regime Aware Users'+'Old Regime Unaware Users')/('Total New Regime Users'+'Old Regime Aware

		Users'+'Old Regime Unaware Users') //MAX(0,'Old Regime Aware Users')/('Total New Regime Users'+'Old Regime Aware Users'+'Old Regime Unaware Users')
183	Regime resources sufficiency	NUMBER('Regime Resource Usage')/'Production regime resources'
184	Total Resource Usage	'Regime Resource Usage'+'Resource Usage'
185	Total resources	'Production regime resources'+'Production resources of the new regime'
186	Total members	'New regime members'+'Old regime members'
187	Efficiency differential	New tech efficiency'/'Old tech efficiency'
188	Total scientists	'New Regime Scientists'+'Current Regime Scientists'
189	Regime theory research	(1-'Regime theory')*MAX(0,'Current Regime Scientists Ratio')*'Regime Total Resources Ratio'*(1-NUMBER('Experimental Observation'*'Perceived crisis'))/1<<yr>>
190	Resource Usage New Regime	MIN('New regime members'*'Outside total members ratio','New Regime Capacity'*'New old capacity ratio')*MAX(0,MIN(1,'Production resources of the new regime'))/1<<yr>>
191	Impact on natural environment	DELAYINF('Regime Environmental Impact','Delay in environmental impact',1,'Regime Environmental Impact')
192	Shift of resources	MAX(0/1<<yr>>,('Membership shift'))*MIN('Production regime resources','New regime resource shortage')*MAX(0,MIN(ROUND('Production regime resources',0.1),1))
193	Resources supply New regime	DELAYMTR('Resource Usage New Regime','Resource supply adjust delay',1,'Resource Usage New Regime')//*'Outside total members ratio'+MAX(0,MIN('New regime resource shortage','New regime members'))/1<<yr>>
194	Membership shift	MAX(0,(1/'Alignment of rules & activities')*('Regulation - Incentives')*'Ratio of users against old rules'*'Compound efficiency differential'*(1/'Incumbent resistance')*(MAX(MIN(1,ROUND('Old regime members',0.001)),0))*IF('New regime members'>100,0,1))/'Time for infrastructure depreciation'
195	Regime Resource Usage	MIN('Old regime members'*'Regime Total Members Ratio','Old Regime Capacity'*'Old new capacity ratio')*ROUND(MAX(MIN(1,'Production regime resources'),0),0.001)/1<<yr>>
196	Regime resource supply	MAX(DELAYMTR('Regime Resource Usage','Resource supply adjust delay',1,'Regime Resource Usage')*ROUND('Regime Total Members Ratio',0.01)+'Old regime resource shortage'/1<<yr>>,0/1<<yr>>)*'Old New users ratio'
197	Scientists Adopting New Paradigm	NUMBER('Regime Transition'*'Current Regime Scientists'*MAX(0,MIN('Current Regime Scientists',1))+'Experimental Observation'*MIN(1,'Confidence in New Regime')*MAX(0,MIN(ROUND('Current Regime Scientists',0.001),1)))/'Time to retrain in new regime'
198	Current Regime Scientists Retire	MAX(0,ROUND('Current Regime Scientists',0.001))/'Years as scientist'
199	New Regime Scientists Die	'New Regime Scientists'/'Years as scientist'
200	Current Paradigm Education	Candidate Scientists'*MAX(0,ROUND('Confidence in Current Regime',0.001))/'Time to train in current paradigm'
201	New Regime Education	Candidate Scientists'*'Confidence in New Regime'/'Time to train in new regime'
202	Rate of Training	Scientists Training'/'Time for education'
203	Possibility of experimental anomaly	DELAYINF('Regime Environmental Impact','Observational delay of regime effect',1,'Regime Environmental Impact')
204	Rate of new theory research	(1-'New theory')* 'Experimental Observation'*'Perceived

		crisis' *'New Regime Scientists Ratio' *'Outside Total Resources Ratio'
205	Paradigm transition	Number of experimental anomalies'^NUMBER('Rate of new theory research')*MAX(ROUND('Confidence in Current Regime',0.001),0)/('Years as scientist')
206	Rate of crisis increase	('Number of experimental anomalies'-'Perceived crisis')/1<<yr>>
207	Experimental observations	MAX(NORMAL('Impact on natural environment','Impact on natural environment'/2,0.5),0)
208	Experimental Observation	IF ('Experimental observations'>'Possibility of experimental anomaly',1,0)/1<<yr>>
209	New tech efficiency change	MAX(('New theory'/MAX(1,'New tech efficiency'))*'Outside total members ratio'*'Outside Total Resources Ratio',0)/('Efficiency improvement delay')*'Regulation - Incentives effect on new tech efficiency'*'New Regime Scientists Ratio'
210	Old tech efficiency change	ROUND(MAX(('Regime theory'/'Old tech efficiency')*'Regime Total Members Ratio'*'Regime Total Resources Ratio',0),0.001) /('Efficiency improvement delay')
211	Alignment replenishment	MAX((NUMBER('Max alignment'-'Rule System Alignment'))-'Decrease alignment'*1<<yr>>,0)
212	Check for zero alignment	MAX(MIN('Rule System Alignment',1),0)
213	Decrease alignment	MAX(0,(1-'Rule system stability'*'Alignment of activities')* MIN('Political pressure'/MAX(1,RUNMAX('Political pressure')),1) *'Check for zero alignment') /1<<yr>>
214	Increase Rule alignment	'Alignment replenishment'/1<<yr>>*'Rule system stability'
215	Coordination of activities	1-STDEV('Rule System Alignment','Rule system stability')
216	Incumbent influence on policy	MAX('Incumbent resistance'-RUNMAX('Window of Opportunity'),0)
217	Pressure on the system	ABS(NUMBER('Rate of change of perception of needs'*'Perception of new needs'+'Political pressure increase'*'Political pressure')*'Ratio of old regime users against rules')
218	Check for WoO	MAX(MIN('Max WoO'-'Window of Opportunity',1),0)
219	WoO close	('Window of Opportunity')/(ABS('New need')+1)/1<<yr>>
220	WoO open	DELAYINF('Pressure on the system','WoO open delay',1,'Pressure on the system')/1<<yr>>*'Check for WoO'
221	Perception of regime effect	DELAYINF('Regime Environmental Impact','Regime impact perception delay time',1,'Regime Environmental Impact') *'New theory'*'INPUT Media influencing public' //'Old regime users'
222	Old regime effect rate	(('Total old regime users')/('Old tech efficiency'))/1<<yr>>*'INPUT Old regime effect scenario'
223	Check for target stability	'Rule system stability'/'Max rule stability'
224	Rule replenishment	MAX((NUMBER('Max rule stability'-'Rule system stability'))-'Rule destabilization'*1<<yr>>,0)*IF (('Perception of new needs')<>0,1,0)
225	Check for zero rule	MAX(MIN('Rule system stability',1),0)
226	Rule destabilization	(ABS('Perception of new needs')*'Ratio of users against old rules'*MIN('Political pressure'/MAX(1,RUNMAX('Political pressure')),1)*'Check for zero rule'*'Switch Rule System Stability')/'Time for infrastructure depreciation'
227	Rule in the making	Rule replenishment'*'Check for target stability'/'Time for infrastructure depreciation'
228	New old users %	ROUND('Total New Regime Users'/('Total New Regime Users'+MAX(0,'Old Regime Unaware Users'+'Old Regime Aware Users')),0.001)
229	New old capacity ratio	'New Regime Capacity'/MAX(1,('New Regime Capacity'+'Old Regime Capacity'))
230	Check investment coverage	MAX('Old Regime Production Capital'/'Regulation -

		Incentives',0)
231	Old capacity decrease	'Old Regime Capacity'/('Time for infrastructure depreciation')
232	Old capacity increase	MAX(('Old capacity decrease')*'Old capital capacity ratio'+('Required old regime capacity'-'Old Regime Capacity')/'Time to develop capacity',0/1<<yr>>)
233	Investment shift	Regulation - Incentives'*'Check investment coverage'/('Time for infrastructure depreciation')*(1-'Incumbent resistance')*(1-'Rule system stability'*'Rule System Alignment')*(1+'Efficiency differential')*NUMBER('Membership shift')*MAX(0,MIN('Old Regime Production Capital',1))
234	New user need	'Old Regime Aware Users'/'Total users'
235	Change in EoS old	('Old Regime Capacity'-'Economies of scale old')/'Time for infrastructure depreciation'
236	Change in EoS new	('New Regime Capacity'-'Economies of scale new')/'Time for infrastructure depreciation'
237	New Old users ratio	ROUND('Total New Regime Users'/('Total New Regime Users'+'Old Regime Aware Users'+'Old Regime Unaware Users'),0.0001)
238	Decrease incumbent resistance	MAX(0,(1-'Alignment of rules & activities'))*'Efficiency differential'*MAX(('Regulation - Incentives')/MAX(1,('Incumbent resistance'*'Old Regime Capacity'))*(1-MIN(1,'Regime Total Members Ratio')),0)
239	Regulate flow	IF ('Competitiveness diff'.'Regime shift direction'>0, ('Check stock coverage'),0)
240	Check users Level	MIN(100,MAX((ROUND('Old Regime Aware Users',0.01))/('Competitiveness diff'.'Competitiveness diff'),0))
241	Total users	'Old Regime Aware Users'+'Total New Regime Users'+'Old Regime Unaware Users'
242	Investment of resources for process improvement production capital	'New Old users ratio'*'Technical solution pilot runs'*'Economies of scale new'
243	Threshold technical feasibility of solution	'Old regime competitiveness'/'Regulation - Incentives'
244	New capacity decrease	'New Regime Capacity'/'Time for infrastructure depreciation'
245	New capacity increase	(('Technical solution pilot runs'/MAX('New Regime Capacity',1))/'Time to develop capacity'*('Investment of resources for process improvement production capital'/MAX('Technical solution pilot runs',1))+'Required New Regime Capacity'/'Time to develop capacity'*'New Capital Sufficiency for Capacity investment')*(1-'New Regime Capacity Shortage')+'New capacity decrease'
246	Regulation - Incentives	(DELAYINF('Political pressure'*(1-'Incumbent influence on policy'),'Delay in regulation effects',1)*'Switch Regulation - Incentives')*'Scope for Regulation Switch' +1
247	Political pressure decrease	MIN('Political pressure',(1-'Perception of new needs'))/'Political pressure change delay time'*(1-'Incumbent resistance'*'Perception of new needs')*'New Old users ratio'*'Switch Political Pressure'
248	Political pressure increase	Perception of new needs'/'Political pressure change delay time'*(1-'New Old users ratio')*'Switch Political Pressure'
249	Level of tech solution diffusion	'Total New Regime Users'/'Total users'
250	Technical solution pilot runs	MAX(ARRSUM('Niche R & D')/MAX('Threshold technical feasibility of solution',1),0)
251	Flow of Financial Capital	'Perception of new needs'*'Regulation - Incentives'*MIN(1,'New regime members')
252	Rate of change of perception of needs	('New user need'-ROUND('Perception of new needs',0.01))/('Need perception delay time')*('INPUT Media influencing public')

253	User Transition	('Competitiveness diff'.'Competitiveness diff'/'Delay in user transition'*'Regulate flow'*'New old capacity ratio'*'New old users %'*(1-'Rule System Alignment'*'Rule system stability')*('Regulation - Incentives'))
254	New regime competitiveness	MAX(1,'Regulation - Incentives')*'Economies of scale new'*'Compound efficiency differential'
255	Old regime competitiveness	Economies of scale old'/'Regulation - Incentives'*IF('Compound efficiency differential'=0,1,1/(0.02+ROUND('Compound efficiency differential',0.01)))
256	Competitiveness diff.Competitiveness diff	MAX('New regime competitiveness','Old regime competitiveness') *'Regime shift direction'
257	Competitiveness diff.New old ratio	'New regime competitiveness'/MAX(1,'Old regime competitiveness')
258	Competitiveness diff.New regime competitiveness	Parent~'New regime competitiveness'
259	Competitiveness diff.Old new ratio	'Old regime competitiveness'/MAX(1,'New regime competitiveness')
260	Competitiveness diff.Old regime competitiveness	Parent~'Old regime competitiveness'
261	Competitiveness diff.Regime shift direction	IF ('New old ratio'>'Old new ratio',1,-1)*IF('New old ratio'='Old new ratio',0,1)
262	User Choice.Competitiveness diff	(1+'Normalised Tech Price Perf Dev')*'Tech Price Perf Ratios'+'Users Ratios'
263	User Choice.Min Tech Price Perf Dev	ARRMIN('Tech Price Perf Dev')
264	User Choice.Normalised Tech Price Perf Dev	'Tech Price Perf Dev'+ABS('Min Tech Price Perf Dev')
265	User Choice.Price Perf ArrSum	ARRSUM('Price Perf Ratio')
266	User Choice.Price Perf Avg	ARRAVERAGE('Price Perf Ratio')
267	User Choice.Price Perf Ratio	Parent~'Perf Price Ratio'
268	User Choice.Tech Price Perf Dev	FOR (i=TechRange|'Price Perf Ratio'[INDEX(I)]-'Price Perf Avg')
269	User Choice.Tech Price Perf Ratios	FOR (i=TechRange|'Price Perf Ratio'[INDEX(i)]/MAX(1,'Price Perf ArrSum'))
270	User Choice.Total Users	ARRSUM(Users)
271	User Choice.Users	Parent~'Niche Users'
272	User Choice.Users Ratios	FOR (i=TechRange|Users[INDEX(i)]/MAX(1,'Total Users'))
273	Niche Required Capacity	'Total Niche Users per Tech'*'User Capacity Conversion Factor'
274	Total Niche Users per Tech	'Niche Users'+'Allocate Potential New Niche Users'
275	Allocate Potential New Niche Users	PRIORITYALLOC('Potential New niche Users',{'Potential New niche Users','Potential New niche Users','Potential New niche Users'},'Niche Users')