Comput Math Organ Theory (2008) 14: 320–349
DOI 10.1007/s10588-008-9032-4

Studying transition dynamics via focusing on underlying feedback interactions

Modelling the Dutch waste management transition

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Published online: 23 September 2008

Abstract The emerging need for societal transitions raises the need for a better understanding of the dynamic nature of large scale societal systems, and therefore the development of an analytical approach for drawing dynamic conclusions based on system's dynamic mechanisms, feedback relationships and interacting components.

The objective of this study is to explore the degree to which System Dynamics as an approach enhances the process of understanding transition dynamics in socio-technical systems. In other words, it is aimed to reveal the type of insights that can be developed about such systems and their dynamic behaviour using the approach, as well as the shortcomings of the approach in this challenging task. In order to do so, a modeling study aiming to understand the underlying mechanisms of the waste management transition in the Netherlands is conducted.

The quantitative model developed is based on the historical case of the waste management transition of the Netherlands, and it portrays issues as the dynamics of actors' preferences, development of infrastructure and environmental consequences of dominant mode of functioning and provides an instance for demonstrating and evaluating the feedback-focused perspective discussed in this paper.

Finally, the paper discusses a set of points regarding the utilized approach, System Dynamics, observed during this study both in general and in the specific context of transitions. In short, System Dynamics stands as a promising approach mainly due to its strength in explaining the source of complex dynamics based on interacting feedback loops, but it also has certain drawbacks in the context of transitions.

Keywords Transitions · System dynamics · Simulation model · Waste management

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1 Introduction

The severity of the problems experienced in the socio-technical systems, and the rising concerns about the sustainability of the current functioning and the structure of the large-scale societal systems requires understanding how to change such systems. Given the interconnection of social and physical/technological components in such systems, these processes of change are complex because these are long-term structural change processes spreading over several aspects of the societal system, such as culture, technology, institutions and infrastructure, and are referred to as *transitions* (Rotmans et al. 2001; Rotmans 2005). Additionally, designing effective interventions in order to steer them is troublesome. These aspects of the transition processes are already discussed in the relevant literature (Berkhout et al. 2004; Geels 2002, 2005b; Geels and Schot 2007; Loorbach 2007; van der Brugge et al. 2005; Unruh 2000, 2002).

This difficulty raises the need for a better understanding of the dynamic nature of such systems. The dynamic complexity of the transition processes that makes them hard to comprehend arises mainly from the way the elements of the societal systems are arranged and the way they interact. The actors in these systems are embedded in a web of feedbacks that make their future actions conditioned to their own and other actors' actions. These feedbacks may come from the technical, social and environmental domains, and some of these feedbacks are slow, whereas others are fast. Coupling this with the multiplicity of the actors in these systems (i.e. multi-actor aspect), a big set of interacting feedback loops with different speeds and impact strengths seems to be in operation. The second aspect of these systems that contribute to their dynamic complexity is the time delays embedded in the system. These delays can be identified between the actions of the actors and their consequences (e.g. capacity increase decisions and the realization of the new capacity installation), as well as in the information diffusion processes (e.g. time to recognize the supply shortage in the market). Apart from these two aspects, these systems also include non-linear interactions among their components. Variable returns-to-scale in technological development, production costs, or learning processes stand as some examples of such non-linearities.

Understanding the dynamics of transitions is crucial in the context of policy making. However, the aspects of societal systems mentioned above (i.e. feedback loops, time delays and non-linear interactions) make it a hard and challenging task. The system boundaries used by the policy makers, which are generally not wide enough to capture some of the important feedback loops, is one side of the problem. Apart from that, misperception of the feedbacks, difficulty in reasoning about causes and effects distant in time (i.e. due to time delays), and failure to make inferences about dynamics of a system that includes even a modest number of feedback loops (i.e. computational burden exceeding mental skills) are other known problems that stand in the way of learning more about the dynamic complexity of these systems. The existence of such problems in reasoning about complex systems is demonstrated clearly in various studies, of which a subset is presented by Sterman (1994, 2000).

When discussing the challenges of understanding the dynamic complexity of systems, Sterman highlights a set of elements crucial in learning about such systems

(Sterman 1994). One of these elements is a set of tools to *articulate and frame issues, elicit knowledge and beliefs, and create maps of the feedback structure of an issue from that knowledge*. The other set of crucial elements are *formal models and simulation methods to assess the dynamics of those maps, test new policies, and practice new skills*. We recognize System Dynamics (SD), which is proposed as an approach for studying systems with dynamic complexity, as an approach that incorporates such elements and evaluate it as having the potential of being a fruitful approach for understanding more about transitions of societal systems.

The main objective of this study is to explore the degree to which SD as an approach enhances the process of understanding transition dynamics. In other words, we aim to reveal the type of insights that can be gathered about such systems and their dynamic behaviour using the approach, as well as the shortcomings of the approach in this challenging task. In order to do so, we conduct a modeling study for a specific societal transition case; the waste management transition of the Netherlands. By using SD, we aim to study, at a high aggregation level, the dynamics of the given transition case in terms of a certain set of actors, their objectives, their interaction with the other components of the system and their decision mechanisms. While doing so, we also aim to look at the process from a wider perspective and evaluate the process, highlighting the advantages and shortcomings of SD approach in this context.

The next section is a brief introduction to SD as a modeling approach. Section 3 explains the objective of this modelling study and describes the modelling process of the waste management case of the Netherlands. Section 4 presents the results of the base run and the sensitivity analysis. The lessons learned in this modeling process are presented in Sect. 5. Section 6 is devoted to the discussion on the assessment of SD based on this modeling study, and to the main conclusions.

2 System Dynamics (SD)

System Dynamics (SD), which is mainly known as a modeling method that relies on differential equations, appeared in the literature by the works of Forrester in the 1960s (Forrester 1961, 1969). However, SD does not only cover how to model a given system, but also how and where to look for the underlying mechanisms of the observed behaviour (i.e. has an embedded epistemological perspective). It would therefore be more appropriate to consider it as *an approach for studying the dynamic behaviour of systems* benefiting from quantitative simulation models.

As an approach for studying the dynamic behavior of socio-economic systems, SD focuses on feedback relations and delays embedded in the system structure. This is clearly expressed by Richardson as follows,

> "The expressed goal of the SD approach is understanding how a system's feedback structure gives rise to its dynamic behavior." (Richardson 1991, p. 299)

A researcher studying a certain (problematic) dynamic system behaviour with a SD perspective will be relying on qualitative as well as quantitative data about the system and the studied behaviour in order to conceptualize the system structure that is influential in the emergence of such a dynamic behaviour. This process basically focuses on identification of important components of the system, their interactions, time-delays and the feedback loops, which are closed sequences of causes and effects (Richardson and Pugh 1961), formed by these interactions (Sterman 2000). Such a depiction of the system constitutes a hypothesis about the structure of the system that yields the observed dynamics. In that sense, the feedback structure conceptualized by the researcher is referred to as the *dynamic hypothesis* in the SD approach. This dynamic hypothesis is tested and updated based on the behaviour demonstrated by the model until it is concluded that a good dynamic mechanism is identified in the system that explains the observed behaviour. SD practitioners use visual conceptualization tools such as *causal loop diagrams* (CLD) or *influence diagrams* (ID) during the construction of a dynamic hypothesis (Coyle 2000; Sterman 2000).

The fundamental epistemological perspective of the SD approach is that the internal causal structure is responsible for the dynamic behaviour to be understood (i.e. the way system components interact that mainly conditions the overall dynamics of the system being observed). Explanations for the observed behaviour come therefore from the system structure itself (i.e. endogenous explanation) in the form of feedback loops, delays and non-linearities embedded in the system, not from single decisions or external disturbances (Richardson 1991). This assumption is key for determining the decisions regarding the system boundary employed in model construction in SD; any component or relationship hypothesized to influence the observed behaviour shall be considered as a part of the system, and the system boundary shall be large enough to cover any feedback loop that is conceptualized to play an important role in the long-term behaviour of the system.

Similar to other modeling approaches, a four stage modeling process (i.e. conceptualization, model formulation, validation and experimentation), followed rather in a recursive than a linear manner (Randers 1980; Sterman 2000), is used in SD. One of the issues that differentiates SD from other modeling approaches is its emphasis on behaviour patterns, rather than numerical accuracy during the validation and experimentation stages (Barlas and Kanar 1999; Yücel and Barlas 2007). This is in line with the focus of SD on understanding the structural cause of the dynamic behaviour, rather than on generating numerical predictions regarding the future behaviour of the studied system, especially because the uncertainty level of numerical prediction increases exponentially when studying long term dynamics.

The focus on long-term behaviour and the emphasis on the system aspects yielding dynamic complexity (i.e. non-linearities, delays, etc.) made SD a favorable approach to be utilized in studying transition dynamics. Despite differences in their application domains, several studies already utilized the approach in exploring transition dynamics (Fiddaman 1997; Homer 1987; Schade and Schade 2005; Sterman 1981; Struben and Sterman 2008).

3 Learning about the Dutch waste management transition

The way waste is handled in the Netherlands went through a significant change over the last four decades, which includes changes in various aspects from the infrastructure used to the formal institutions about the issue. In that sense, this long-term change in the waste management system is accepted as a transition. Although historical narratives of the process that are mainly descriptive in nature are available, a proper understanding about the underlying dynamics is lacking.

In this modeling study we aim to develop some insight about the way the waste management system evolved over time, and try to explain the dynamic behavior in terms of the way the system components were interacting. In doing so, we will be using SD as an approach, and trying to incorporate important elements and their interactions of the system in a quantitative model. By using the model, we will be able to see various interactions and developments mentioned in the narrative of the case simultaneously at work. The insights to be developed using the model about the underlying mechanisms of the system behavior are important in the sense that they have the potential to be *transfered* to other transition contexts (e.g. mobility, energy, health, etc.).

The following sub-section will present a brief summary of the developments observed in the Dutch waste management system (for an extensive description of this transition, which served as the basis for this study, please refer to Loorbach (2007)). Next, the model developed for the problem is presented. Last two sub-sections are devoted to the model behavior analysis and conclusions regarding this modeling exercise.

3.1 Waste management transition in the Netherlands

The second half of the 20th century can be characterized with a significantly growing amount of waste as a direct consequence of the new lifestyle and economic system, promoting increased consumption. In line with this, the 1960s brought enormous amount of waste, especially synthetics in the form of packaging materials and disposable products. Additionally, chemicals and toxic substances were also part of this stream. By that time, it was already socially and institutionally assumed that the government should be responsible for the waste management (Collection-treatment-disposal). An almost exponential growth of waste to be handled was exerting serious pressure on the existing waste handling system. By the end of 1960s, the dominant way of dealing with this waste was landfilling.

The environmental concerns being raised at a global scale and the high volume of waste being landfilled triggered the change in the social awareness during 1970's regarding the environmental consequences of the landfilling practice. Meanwhile, some significant changes in the governmental arena were also taking place parallel to the changes in public opinion. The law on waste was pronounced and a method for ranking different types of waste management—better known as the "Lansink's Ladder"—was made public. The introduction of the law on waste forced the acceptance of a separate waste collection system by waste handlers. Again recycling and re-use emerged in the form of alternative circuits for glass, paper, clothes and metals. By the end of the 1970s waste collection and transportation were organized as municipal service.

In the 1980s the social awareness increased due to deforestation and acid rain while searching for a healthy environment. Additionally, the Lansink's Ladder became the basis of a law pronounced in the mid 1980s. Because of that law, incineration became the method promoted by the government for waste disposal, which increased the investments in this kind of facilities.

In the 1990s, the institutional and market structure, the physical infrastructure, the practices and culture changed in order to improve efficiency and economic benefit from the waste management. Not only the waste practices in households but also the waste management system itself diversified, making possible an intensive use of the different waste flows and a shift from landfilling practices to incineration and reuse at the waste management level, and recycling at household level at the end of the 1990s. This situation did not impede the growth of total waste production.

At the beginning of the 21st century, the Dutch waste management system can be characterized as a re-use dominated system in which landfilling is the least utilized option. At the same time, market developments, organizational aspects, policies and individual practices reached a temporal equilibrium.

3.2 Model description and specification

Based on the case study summarized above, three major means of managing waste, which will be referred to as *options*, are identified in the Dutch waste management system, namely landfilling, incineration and re-use. As mentioned before and also highlighted by other authors working on societal transitions (Homer 1987; Struben and Sterman 2008), a wide system boundary is needed in order to properly capture the ongoing dynamics in a transition process. Hence, apart from the fast dynamics at the decision-makers' level, our model also incorporates slower environmental dynamics. Briefly, the decision-makers stand at the core of the conceptualization, and the model covers the information flow, preference change and decision change dynamics (i.e. decisions regarding feasible waste management options) of relevant actors in the waste management system. These constitute the fast processes in the model. Additionally, the model also incorporates the processes of infrastructure development and endogenous technological development (e.g. improvements air and soil pollution caused per unit of waste processed) regarding available waste management options, which are basically driven by the decisions and resource allocations of the decision-makers. Finally, the dynamics of aggregate space used for waste, air pollution and soil pollution levels are considered as the relevant slow processes in the system. This briefly depicts the boundaries of our model.

We utilize a conceptual framework that guide us in mapping the obtained information about the system for the dynamic hypothesis we develop regarding the observed dynamics of the system. Due to the possibility of recognizing most of its aspects in other transition processes, a general discussion on the elements of this framework will be followed by the specification of these elements in the case of the Dutch waste management transition. The following subsections aim to provide a summary of the main assumptions, the boundary and the important formulations of the model. The full set of model equations and the parameter values used, in the form of Vensim model equations, can be found in the electronic supplement of this article.

3.2.1 Multi-actor nature of the system

Actors' decisions result in a change in the system and the nature of the change varies depending on the type of the decision being made. A decision can be related to e.g.

"using public transport", or "investing in public transport". Based on the actors' decision, the impact on the societal system being considered will vary. This results in the need for defining actor types based on the impact of their decisions on the system. Based on an inductive study using a set of empirical transition case studies (van der Brugge et al. 2005; Geels 2002, 2005a, 2005b; Loorbach 2007), the following four actor types, or actor roles are identified;

- Providers: Actors who provide and maintain the means for fulfilling the societal function and whose decisions influence the means of provision (e.g. infrastructure). This includes maintaining the infrastructure, supplying a certain artefact, investing in new options, etc. The societal function being defined as the management of the waste produced, the providers for our specific case are the contractors that work with local municipalities and providing them waste management services (e.g. incineration, landfilling).
- Regulators: Actors whose preferences regarding the means for fulfilling the identified function influence their use via regulations (e.g. a government agent providing subsidies or taxes). The decisions of these actors have an impact on, for example, laws and regulations regarding the available options. The representative of the regulator-type actor in the waste management transition is the central Dutch government.
- Practitioners: Actors who actually *use* the available means for fulfilling the societal function of concern. Local municipalities, being responsible of managing (i.e. planning and organizing waste collection and removal) the waste collected, are identified as the main practitioners of this case.
- Supporters: These actors' preferences regarding a means for fulfilling the identified function may influence the way it is perceived as more or less favorable by other actors. However, their influence on the perception of the means, or the means themselves is indirect. The decisions of this actor group to support or oppose an option at the most general level are thought to be influencing the social perception regarding that option. In the Dutch waste management case, the supporters are used to represent the common opinion in the public regarding the waste management options.

As mentioned above, the categorization of the actors is done on the basis of differences in the nature and consequences of their decisions. Going over the actors covered in this model, the central government is responsible for the institutional setting about the waste management issue. In reality this is done via laws, regulations, subsidies, etc. In the model, a set of variables represent the degree of support for the options in the regulatory arena. In each time period, the regulator (i.e. central government) is conceptualized as deciding on how much to alter this state of regulatory support (i.e. increase/decrease the regulatory support for an option). The decisions of the practitioner (i.e. municipalities) is conceptualized to be about how much to alter the shares of each option in waste handling (i.e. percentage of total waste to be handled via a particular option), while in reality this is done by hiring more waste contractors of the preferred option for waste handling and less of the least preferred option. On the provider side, decisions are related to capacity management and they decide on how much to change their investment behavior, which is conceptualised as the percentage of capital investment allocated to a particular option. Finally, the supporters are assumed to have an opinion about the convenience of each option, and their instantaneous decisions are about in which way and how much to change them; however their change in opinion is conceptualised in a rather continuous way. The formulation of these decisions will be discussed in the following section.

Apart from being heterogenous in terms of the nature and impact of their decisions, actors naturally have differing objectives, which is also highlighted as the *multi-actor* nature of the transitions (Rotmans 2005). Hence, in the model each actor is assumed to have a set of objectives, and makes decisions according to those objectives. Table 1 summarizes the objectives of each actor as well as the monitored attributes of the system used by those actors in assessing their situation in relation to these objectives. For example, one of the objectives of the government (i.e. regulator) is identified to be complying with the public opinion as much as possible. So, in assessing the degree to which its decisions fulfill this objective, the actor uses the information it has about public support for each waste management option.

3.2.2 Formalization of the decision process

In the way actors are conceptualized in the model, the actors are facing a multi-objective decision process. Referring to the decision analysis field (Keeney and Raiffa 1993; Keeney and Gregory 2005), in order to formalize such a multi-objective decision making process two fundamental components need to be specified; a *preference structure* for the actor and *attributes* that will be monitored by the actor to evaluate the consequences of decisions.

In the formalization of the conceptualized decision process, the *attributes* are identified as the properties of the available options that represents the degree to which an option serves a particular objective of the actor. In other words, for each objective, an actor uses a single quantifiable attribute related to an option in order to evaluate the consequences of choosing that option in terms of that specific objective. For example, when considering a mobility-related problem, CO_2 *emission performance* of hybrid cars may serve as the attribute of that option to be used regarding the objective of *reducing global warming impact*. The relevant attributes for each actor for each objective are already given in Table 1.

The formalization of a preference structure (i.e. formalizing a value function for each actor) is not a straightforward task, and the purpose is to obtain a suitable function for the conceptualization of this transition problem. Considering the main objectives of this work, a considerably simple value function is formulated for the actors. Let d represent a particular plausible decision for the actor (e.g. buying a hybrid car), and x_{di} represent the expected level of attribute i (e.g. CO_2 emitted per km traveled), which is related to the ith objective (e.g. reducing global warming impact) of the actor, to be realized as a consequence of decision d. Then we assume that the actor values the consequences of the decision d as follows;

$$V_d(t) = \sum_i \lambda_i(t) v(x_{di}) \quad (1)$$

where $v(.)$ is *the component value function* (Keeney and Raiffa 1993). These functions are used to evaluate the consequences of decisions for each objective in an

Table 1 Objectives of the actors and related attributes monitored

Actor	Objectives	Attributes monitored
Government	Maximize compliance with the public	Public support for the options
	Minimize soil pollution impact	Soil pollution performance of the options
	Minimize air pollution impact	Air pollution performance of the options
	Minimize space used for waste management	Space required per waste processing capacity
Local municipalities	Maximize compliance with the public	Public support for the options
	Minimize soil pollution impact	Soil pollution performance of the options
	Minimize air pollution impact	Air pollution performance of the options
	Minimize space used for waste management	Space required per waste processing capacity
	Maximize use of available processing cap	Usage of available processing capacity
	Maximize compliance with regulations	Regulator support for the options
Waste contractors	Maximize compliance with the regulations	Regulator support for the options
	Minimize supplied-capacity gap	The gap between demanded and supplied capacity of the options
Public/NGOs	Minimize soil pollution impact	Soil pollution performance of the options
	Minimize air pollution impact	Air pollution performance of the options
	Minimize space used for waste management	Space required per waste processing capacity

isolated manner and the decision that yields the best possible attribute level yields a value of 1 (i.e. $v(x_{best}) = 1$). All decisions are evaluated in a range of [0, 1] according to these *the component value functions*. λ_i's in the formulation represents the *weight of the objective i* for the actor, and can be assumed to be a consequence of the norms and preferences of that particular actor. Considering the time horizon and the nature of transitions, these weights are defined to be dynamic in order to capture probable shifts in norms and preferences of the actors. Due to the dynamic nature of these weights, a certain decision that was favorable once, might become unfavorable in the future.

Despite its simplicity, the dynamic nature of the value functions of the actors stands as a powerful representation that may reveal interesting dynamics in terms of transitions. In the following sections the factors that are influencing these value functions will also be discussed briefly.

The outcome of the value functions are used to change the decisions[1] of the actors. For example, in the case of waste contractors the instantaneous decisions are assumed to be the percentage of new capital investment allocated to the options.

In the model, the change in decisions is formulated in the form of bidirectional change equations. An example of these equations is given in (2), which represents the rate of change in the investment percentage for landfilling ($I_{land}(t)$);

$$\frac{dI_{land}(t)}{dt} = s_{reuse,land}(t) + s_{inc,land}(t) - s_{land,reuse}(t) - s_{land,inc}(t) \tag{2}$$

where $s_{i,j}(t)$ represents the shift from option i to option j at time t and specified as follows;

$$s_{i,j}(t) = H(V_j - V_i)[\alpha.(V_j - V_i).I_i] \tag{3}$$

where $H(.)$ is the Heaviside functions (i.e. $H(x) = 1$ for $x > 0$, and $H(x) = 0$ otherwise), V_i is the value attributed to option i, and α is a constant representing the normal fractional change. Hence, when the actor attributes a higher value to choosing landfilling compared to incineration (e.g. $V_{land} > V_{inc}$), $s_{inc,land}$ is expected to be positive, whereas $s_{land,inc}$ will be zero due to Heaviside function. Consequently, the change in the percentage of investment to landfilling (e.g. $\frac{dI_{land}(t)}{dt}$) will be positive.

Regarding the equation given above, almost identical formulations are used for each actor type. The only customization in the equation that differs among actors is the constant that determines the speed of change in the decisions for each actor (i.e. α). Additionally, one important assumption about (3) is related to the status-quo seeking nature of the actors; if two available options are evaluated to be equally desirable (i.e. $V_i \simeq V_j$), no significant change is observed in the decisions of the actor. This implies that in order to trigger a significant change, an alternative option has to outperform the current favorite option of the actor.

[1] At this point it is important to emphasize that considering the aggregate nature of our actors, the decisions of the actors are not discrete, as choosing whether to use landfilling, or not. The modeled decisions are more like resource allocation decisions (i.e. what percentage of available resources shall be allocated to a given option?), and are continuous in nature.

3.2.3 Rationality of the actors

In the model the actors are formalized as agents making decisions based on the aggregate performance of the societal system, the attributes of the options and also the decisions of the other actors. The previous section briefly discussed the evaluation and decision making process. Despite the rational nature of the depicted decision making heuristic, the information used by the actors during the decision making process is not precise and complete. This is attained by introducing perception delay structures in the model. In using such structures, the assumption is that actors may use only the information they have already recognized (e.g. perceived operating cost of hybrid car), rather than the actual and precise information (e.g. actual operating cost of the hybrid car). The used formulation representing the perception delay is an information smoothing formulation[2] widely used in SD practise;

$$\frac{d\hat{x}_{ij}(t)}{dt} = \frac{x_i(t) - \hat{x}_{ij}(t-dt)}{pd_j} \tag{4}$$

where $\hat{x}_{ij}(t)$ is the perceived level of information x_i that can be used by the actor j in decisions, and pd_j is the perception delay of the actor.

Via introducing delayed access to information, the actors have limited access to precise information, and this imprecise information bounds and limits their rationality in the decision making process. In other words, the actual world and the world perceived by the actors are decoupled in the model. Additionally, the introduced mechanism also results in an information heterogeneity among the actors in the modeled societal system, which yields heterogeneous responses. Finally, such delays in the diffusion of precise information, which can be in favor or against further acceptance of an option, play an important role in the societal responses towards innovations in transitions. In that sense, the model is expected to capture, at least at some level, the dynamic richness caused by this information diffusion process.

3.2.4 Feedbacks as the driver of change

As mentioned before, the dynamic complexity of the societal systems stem partially from the multiplicity of slow and fast feedback loops that exist in the system. Keeping the relevant actors (e.g. policy makers, users, etc.) as the reference point, we identify three major types of feedback interactions that condition the transition dynamics of societal systems (see Fig. 1).

1. Feedbacks within the social domain: The actors constitute the social component of the socio-technical system under consideration. Apart from other information, the actors also care about what other actors are doing. According to Coleman (Coleman 1990), actors, as socialized elements in the system, influence each other by means of interdependent dynamics. These dynamics result in a particular choice at an aggregate—system—level depending on the particular set of actors in the system. This means that the aggregated behaviour of the

[2] In fact, this formulation is equivalent to the *exponential smoothing* used in forecasting applications

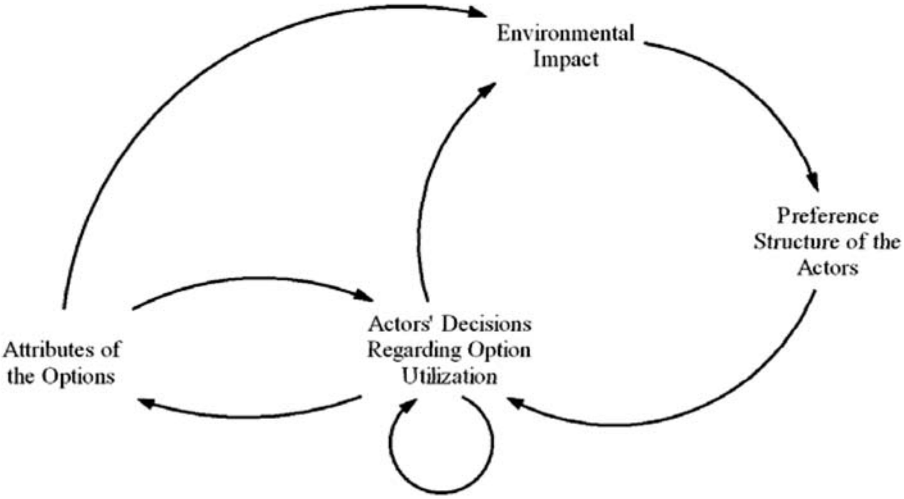

Fig. 1 Major feedbacks hypothesized to be influential in transitions

actors influence each actor's decisions and the consequences of all these decisions affect the behavior of each actor in the system; closing the feedback loop and defining the direction of the transition. For example, the diffusion of a particular practice among users (e.g. *practitioners*), would make it more desirable for the potential adopters and increase their likelihood of giving a decision towards adopting it. Discussions on the existence of such a mechanism is quite common in the diffusion of innovations literature and referred to as *neighborhood effect* or *word-of-mouth effect* (Mahajan and Peterson 1985; Mahajan et al. 2000; Rogers 1983), among others. Additionally, increasing public support for a particular option may induce a *regulator* decision (e.g. subsidy provided by central government) in favor of an available option (e.g. bio-fuels), which may further change the diffusion dynamics of that option. A very similar feedback exists in the model connecting the decisions of the *supporter* and the *regulator* groups, the supporter group acting as the controller of the regulator's actions.

2. Feedbacks between the social and the technological/physical components: The technological/physical component (i.e. infrastructures, artifacts, etc.) has its own internal dynamics and these dynamics are influential regarding the actor decisions in a transition process (e.g. number of refueling points related to the hydrogen car usage decisions). Coupling the dynamics of the social and technological components is therefore vital for studying transitions. In this formalization, a preliminary attempt towards accomplishing such a coupling in a simplified manner is made. For example, it is assumed that the decision of a *provider* towards a particular option improves the carrying capacity related to that option (e.g. number of charging stations for electric cars). On the one hand, a decision of a *practitioner* towards using an option results in economies-of scale dynamics and hence improves the properties of the options (e.g. price of electric cars). On the other hand, increased utilization of an option by *practitioners* causes a load on the carrying capacity of that option, hence may result in deterioration of some attributes of an option.

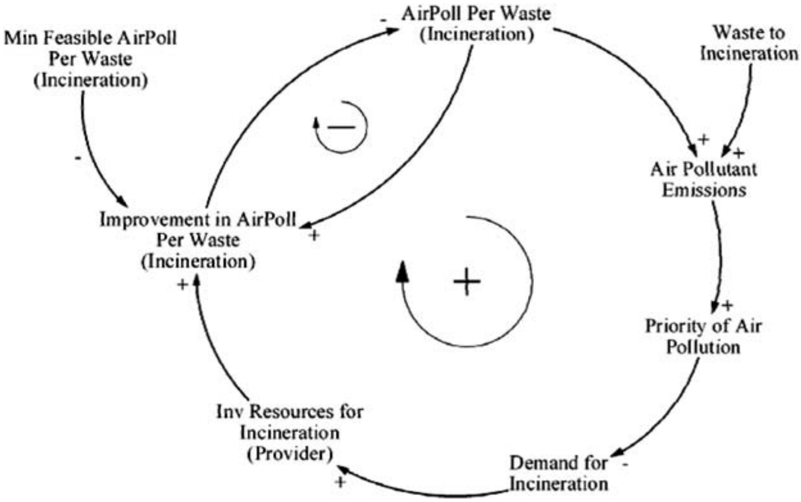

Fig. 2 Feedback loop driving technological development in the model

As an example for such a case, consider the average passenger per vehicle as the attribute that actor cares about public transport option. Increased usage of the option results in an increase in this attribute, which makes the option less attractive. As it should be expected, all of these changes feed back into the actors decision processes in the form of dynamic information related to the available options and influence their future decisions.

In our specific case, we can talk about two examples of such feedbacks. One of them is about the performance enhancement of the options (e.g. air pollution per unit of waste incinerated). More investment in the incineration option triggers faster performance improvements (assuming more investment will bring about more research and development spending). This, in turn, puts incineration to a cleaner position compared to other options. Increasing demand for cleaner incineration triggers further investment to the option. This feedback depicts the success-to-successful type of feedback loop in this specific context. This feedback is coupled with another feedback loop that controls the development process and leads to decreasing returns in technological development. Figure 2 depicts both of these loops. The second example of this type of feedback is mainly responsible for capacity-demand balance in the system. Unsatisfied demand for a waste management option triggers capacity installations. The increase in the capacity reduces the unsatisfied demand, hence leading to less investment to the option.

3. Feedbacks between the social component and the natural environment: This type of feedback can be characterized as the *limits-to-growth* type referring to the widely discussed work of Meadows et al. (1972). The stress on the natural environment due to the way a societal system operates may exceed the carrying capacity of the environment and this may initiate a need for transition in the way societal system performs. A considerable majority of the problems contemporary societal systems are facing are due to the changes occurring in their natural environment due to the existing pattern of interaction between the environment and

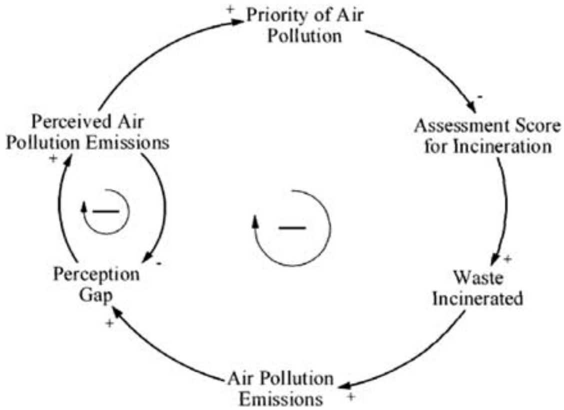

Fig. 3 Feedback loop driving technological development in the model

the societal system. Generally these significant changes may act as the initiator of a transition process. In short, the way a societal system operates feeds back into the system in the form of environmental problems and may result in alteration of the current mode of operation in the long run. As mentioned before, the model includes attributes of the options regarding their performances related to the relevant issues (e.g. air pollutant emissions of waste incineration option). Coupling this information with the decisions of the actors related to utilization of the options allows the model to capture aggregate level impact of the societal system on its environment (e.g. total air pollutant emissions), and then trace the environmental consequences of such an impact (e.g. increasing air pollution). These consequences are perceived by the social component with a delay and may result in a shift in preference structure (i.e. λ_i's in the value function) of the actors. This in turn may initiate a change in the way societal system performs.

In the waste case, three environmental issues are identified as relevant; space occupied for waste handling sites, land pollution, and air pollution emissions. Coupling the attributes of the options regarding these issues (e.g. space required per waste handling capacity, pollutant emitted per unit waste processed) with the amount of waste handled via each option, it is possible to represent the aggregate consequences of the waste system's operation. This information is perceived by the actors over time and as mentioned before may alter their value functions, resulting in the feedback loop depicted in Fig. 3.

The way value functions of the actors change is formalized as follows, going over the case regarding the space issue affecting the practitioner (i.e. municipality);

$$\lambda_{mun,space}(t) = f\left(\frac{\hat{y}_{space,mun}(t)}{\hat{y}_{space,mun}(t_0)}\right).\lambda_{mun,space}(t_0) \tag{5}$$

where $\hat{y}_{space,mun}$ represents the information that actor (i.e. Municipality) has about the environmental impact (i.e. space used for waste management), and $\lambda_{j,i}$ is the priority of actor j for objective i. Assuming that there will be a decreasing-rate of return in the response to the environmental impact levels, $f(.)$ is an S-shaped function and it represents the effect of change of the level of environmental attributes relative to their initial levels on the related priorities of actors. Considering the given space-municipality example, when the space occupied for waste management (e.g. landfilling sites) increases compared to its initial level, this formulation yields an increased priority for the space-related objectives of the municipality in its value function.

4 Model output

The simulation model constructed for the selected case mainly aims to capture the dynamics of the preferences of the four major actor/actor groups regarding the waste management options and their priorities related to the relevant objectives identified in the case. The model behavior spans a time horizon of three decades from 1970 to 2000.

The discussion of the model output is made from the point of view of the *regulator*, as a sample interpretation of the model's output. Considering the space constraints, other actors' behaviors will be discussed more briefly. For the *regulator*, a detailed discussion of the observed dynamics is presented as well as the underlying feedback mechanisms.

4.1 Reference run

As mentioned before, the *regulator* in the model has a set of objectives; to minimize the environmental impact (e.g. space used, soil pollution and air pollution) and to comply with public opinion as much as possible. Apart from the public opinion case, the priorities of these objectives are dynamic in the value functions of the *regulator* (see (1) for the value function).

Figure 4 gives the change in the priorities of these objectives for the actor during the model run. These show that at the beginning of the run the most important issue for the actor is the *used space*. In the first decade of the run, *used space* and *soil pollution* issues are gaining more importance for the regulator, hence the priorities for the relevant objectives are increasing. The environmental impact of the waste management system explains this priority change. Figure 5 summarizes the change in the aggregate soil pollution, the air pollution emissions and the land used for waste management. In the first quarter of the model run, a significant increase in the soil pollution and also in space allocated to waste management are observed, mainly due to the dominance of landfilling as the waste management option as well as the increase in the amount of waste to be managed. As a consequence of the aforementioned changes in *regulator's* priorities, the landfilling option is no longer evaluated to be comparable to other available options, and the *regulator* slowly shifts away from the landfilling option towards the reuse and incineration options (Fig. 6).

Parallel to the shift in the *regulator's* preferences, the amount of waste being incinerated demonstrates a significant increase during the second decade of the run. Since

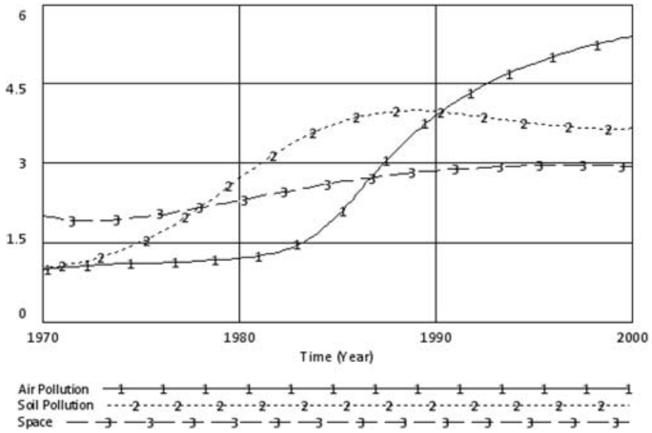

Fig. 4 Priorities of the *regulator* for different objectives

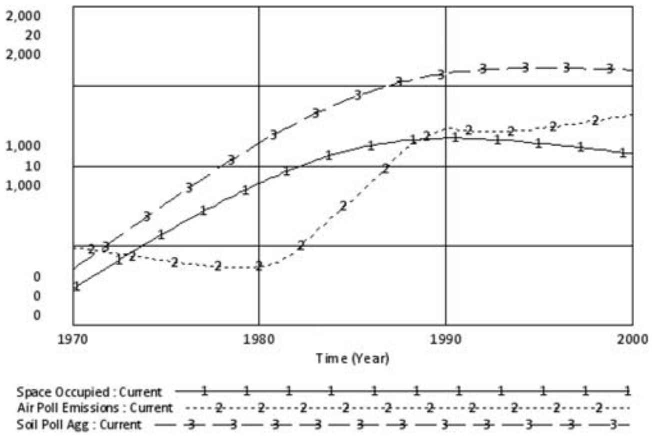

Fig. 5 System's aggregate environmental impact

incineration is a significant source for air pollutant emissions in the model (i.e. worst performing option in terms of air pollution objectives), the environmental impact of the waste management system regarding air pollution is observed to be as in Fig. 5. The increase in the air pollutant emissions induces a change in the priority of the air pollution related objectives of the *regulator* (Fig. 4). This change in the actor's value function (i.e. change in λ's) results in a worse evaluation for the incineration option around the end of second decade.

These changes in the option evaluation influence the dynamics of the option preferences in the regulatory arena (i.e. which options are supported and how much they are supported in the regulatory arena). The model output related to the preferences regarding options in terms of desired percentage of the waste to be processed via a given option is given in Fig. 6. As it can be seen, landfilling loses its position in the regulatory arena and, by the end of model run, it stands as an undesired option. On the

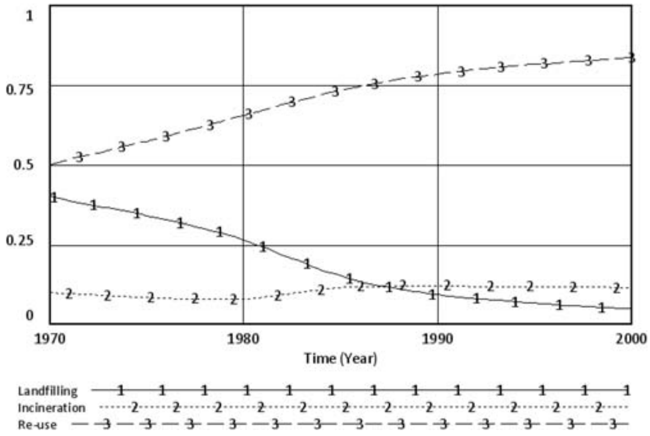

Fig. 6 Waste allocation percentages targeted by the *regulator*

other hand, incineration experiences an increase in preference until mid-80s, which is mainly due to its relative advantage in the soil pollution and space demand issues. And finally, it loses the comparative advantage due to rising air pollution issue, and a stabilization is observed towards the end of the model run.

Up to this point, only the behaviour of the actor is discussed without referring to the underlying feedback mechanisms. Figure 7 presents a simplified[3] causal-loop diagram (CLD[4]) showing five feedback loops influencing the observed behavior of the regulator. The loops are numbered from 1 to 5, and each link is labeled with the number/s of the loop/s it belongs to in order to facilitate the understanding of the diagram.

At the beginning, the loop #1 (L1) exerts some control over the level of soil pollution (i.e. more soil pollutant causes more pollutant degradation per unit time, which in turn decreases the soil pollutant level), which can be seen as a balancing act against the increase of the soil pollution level. However, as a consequence of the increase in

[3]The discussion in the CLD is limited to the issues of soil pollution and air pollution. Although there also exist feedback loops regarding the space issue, their behavior and impact are quite similar to the ones related to the soil pollution. For the sake of clarity, the CLD contains elements summarizing the actual model variables and presents interactions in a more compact form, avoiding an excessive level of detail of the actual model variables.

[4]Causal Loop Diagrams (CLD) or Influence Diagrams (ID) present important variables of the system and have arrows—links between variables—indicating a positive or negative influence of one variable on another (Sterman 2000). Besides individual links, there are also different types of feedback loops; positive (or reinforcing) loops and negative (or balancing loops). A feedback loop is characterized as negative if the number of negative individual links constituting that loop is odd; as positive, otherwise. As it can be understood from the name, positive feedback loops reinforce any change in the loop while negative feedback loops balance or counteract any change in the loop. Assuming that only one feedback loop is passing through a particular variable, if it is assumed that a variable's value in the loop is increasing, the loop will reinforce this effect in time, and the variable's value will continue increasing even faster in the case of positive loops. Following the same example, the increase in a variable will trigger a balancing behaviour via a negative feedback loop, and an increase rate of the variable will decrease until rate of change vanishes.

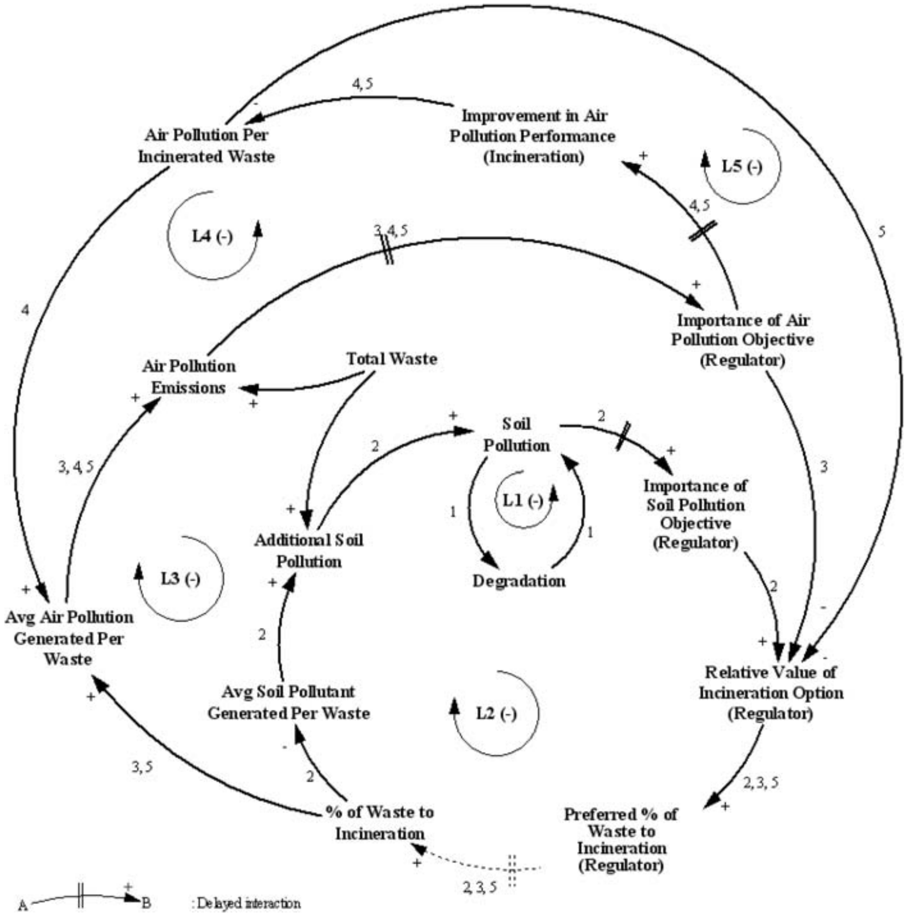

Fig. 7 A simplified CLD of the feedback mechanism underlying regulator's behavior

the total waste to be handled, the growth in the soil pollution exceeds the levels that can be suppressed via degradation mechanism. The observed increase in soil pollution triggers L2, the second balancing loop in the diagram. According to this loop, an actor changes its priorities with a time delay following the recognition of the increase in the soil pollution. The actor therefore changes the assessment of the options, and incineration becomes more favorable. This induces further changes for other actors. For example, as a consequence of changing regulations for supporting incineration, it becomes more favorable for the *provider* and a shift in investment towards incineration starts. The *practitioner* also presents a similar change, shifting its practice more towards the incineration option. Via these mechanisms[5] the percentage of waste be-

[5]Dashed linked in the CLD indicates that the relationship is not direct between those two variables, but the variable at the tail influences the variable at the head via other structures in the model that are omitted in the diagram.

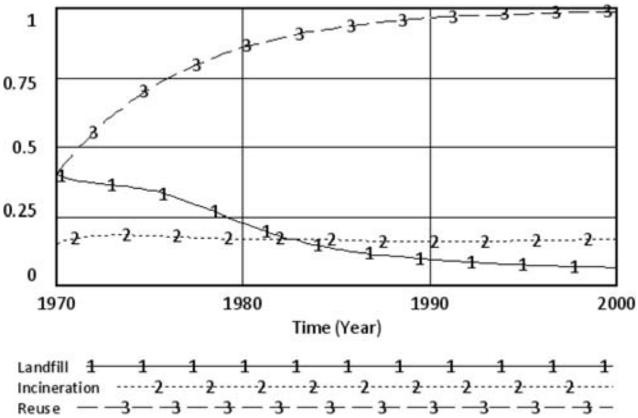

Fig. 8 *Public* preferences for available options

ing incinerated changes after a delay, which in turn, slows down the growth in the soil pollution.

In the absence of other loops, the expected consequence would be that L2 will drive the system to a point where the desired percentage of landfilling for the *regulator* is zero without losing any pace. However, before that point is reached other feedback loops are triggered in order to balance the shift to incineration driven by L2.

The shift to the incineration results in a significant increase in the air pollutant emissions. This triggers L3, which tries to balance the dynamics caused by L2 through increased priority of the *regulator* for air pollution. The consequence of the activation of L3 is the worsening of the evaluation of the incineration option and a decrease in the pace of the shift in the *regulator's* preferences towards incineration. However, the activation of L3 initiates other two counteracting loops; L4 and L5. They are both related to the performance improvement mechanism, activated as a consequence of the air pollution issue that is gaining importance in the regulatory arena. These loops can also be interpreted as the defensive mechanisms of the incineration niche to keep itself as a favorable option in the system. L4 balances the rise of air pollution level that was increasing due to the shift towards incineration. On the other hand, L5 attempts to balance the decrease in the assessment score of the option due to a gain in priority of the air pollution issue.

Although the discussion above can be extended considering the loops related to the reuse option and the space issue as well, it illustrates adequately the interplay between the landfilling and the incineration options in the regulatory arena.

As it was mentioned before, a summarized explanation of the behaviors of the other actors is presented subsequently. When we consider the behavior of the *public* actor, we observe similar dynamics related to the priority of the issues; air pollution is becoming an increasingly important issue and dominating other issues in the second half of the run. This in turn results in the changes regarding public opinion about available options presented in Fig. 8. One difference that needs to be highlighted is the fast preference change of this actor compared to the regulator. Considering that these dynamics represent opinion change, it is reasonable to observe faster changes compared to the changes in the regulations.

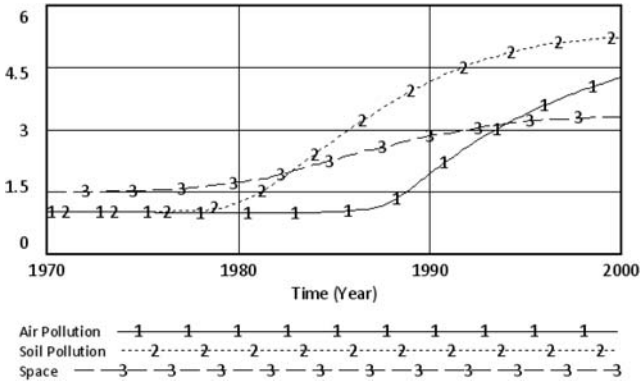

Fig. 9 Priorities of the *practitioner* for different objectives

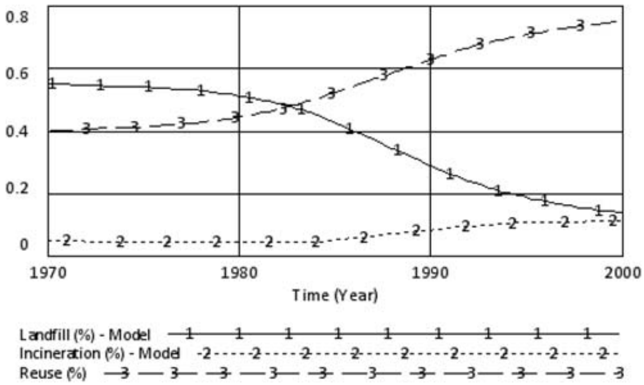

Fig. 10 Percentage of waste allocated to different options by the *practitioner*

Two graphs summarizing the dynamics related to the *practitioner* actor (i.e. municipality) are given in Fig. 9 and Fig. 10. Looking at the latter one, which represents the percentage of total waste managed by the means of each option, it can be said that the system, initially starting from a stable option composition, converges to another stable composition of options after significant dynamic changes. Hence it seems reasonable to state that a transition is close to being completed at the end of the model run.

The model output given in Fig. 10 is one of the very few for which historical time-series data can be obtained. Unfortunately, the accessible precise information about the Dutch waste management system goes back only to 1985. When the model generated output is compared with this historical data (see Fig. 11), it can be concluded that model output is successful in replicating the historical trends. Although there are some numerical deviations, considering that the main goal is to obtain a pattern-based fit rather than a numerical fit, the model output is evaluated to be satisfactory.

Finally, the behaviour of the provider is represented in the following figures that represent the installed processing capacity (Fig. 12) and the percentage of the total

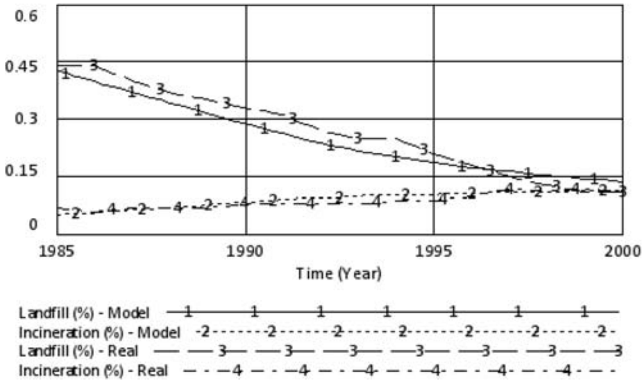

Fig. 11 Comparison of model output for waste allocation percentages with actual data

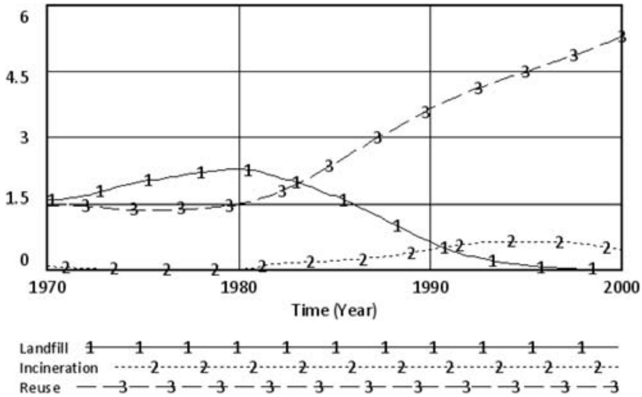

Fig. 12 Percentage of capital investment allocated to options by the *provider*

investments allocated to each option (Fig. 13). Due to the lifetime of the existing waste processing capacity, it takes some time to observe a decrease in the landfilling capacity even after investments for this option have ceased. Another point worth mentioning is the behaviour of the investments to incineration. By the end of the run, a significant decrease is observed. This behaviour is basically due to the fact that the installed capacity around that time seems to be satisfactory for handling the incineration demand coming from the practitioner.

4.2 Sensitivity analysis

One of the key features of SD approach is its position favoring the inclusion of soft variables into the model at least at some level, rather than totally ignoring them due to their incommensurability. This was also the case with our model. A concept like "*actors' priorities for objectives*" was a hard-to-quantify concept, but at the same time it was too important to ignore. Hence, based on the qualitative data presented by Loorbach (2007) we come up with an ordinal ranking of these priorities, and then

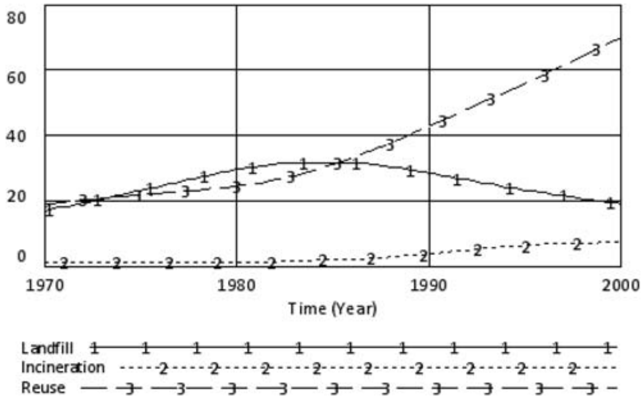

Fig. 13 Available processing capacity regarding different options

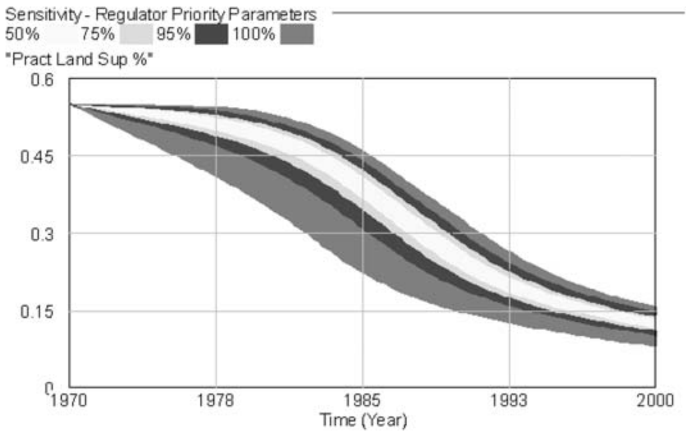

Fig. 14 Waste % to landfilling—sensitivity to initial values for *regulator* priorities

used a priority scale with the range of [0, 5] to quantify them in a consistent way with this ranking. However, it is possible to come up with several quantifications consistent with the same ordinal ranking. Hence, we conducted a sensitivity analysis on the initial values used for the priorities. In this multivariate analysis,[6] the numerical values of the parameters are randomly chosen in a consistent way with the ordinal ranking. In this way, 1000 replications are performed and the change in the observed behavior patterns is studied. Results of a sample analysis (e.g. initial priority values for the regulator) are presented in Figs. 14 and 15.

We have also conducted a sensitivity analysis for the actor-specific delays in changing their priorities. The parameters belonging to all actors are altered concurrently in a multivariate analysis, and as a consequence of 1000 runs, the results in Figs. 16 and 17 are obtained.

[6]For this analysis Multivariate Sensitivity Analysis feature of the simulation software, Vensim, is used.

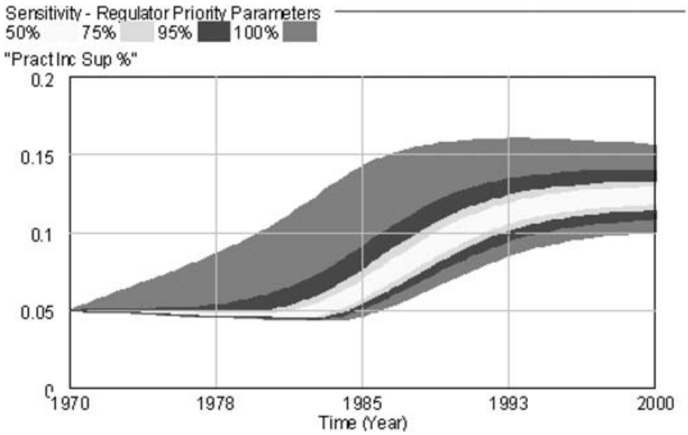

Fig. 15 Waste % to incineration—sensitivity to initial values for *regulator* priorities

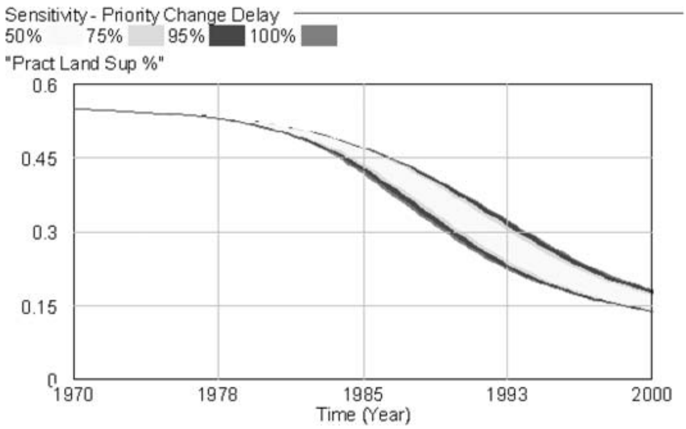

Fig. 16 Waste % to landfilling—sensitivity to priority change delay

Another quantification related problem came up with an aggregate index representing the air pollution performance of the options. Hence, we utilized a similar sensitivity analysis for these values. The outcome of the analysis regarding air pollution related parameter values are given in Figs. 18 and 19.

Based on the results obtained during the sensitivity analysis, it can be concluded that, despite sensitivity in the numerical results, the pattern-wise sensitivity of the model is low, which indicates that the long-term behavior observed is strongly conditioned by the feedback structure modeled, rather than some individual variable values or randomness.

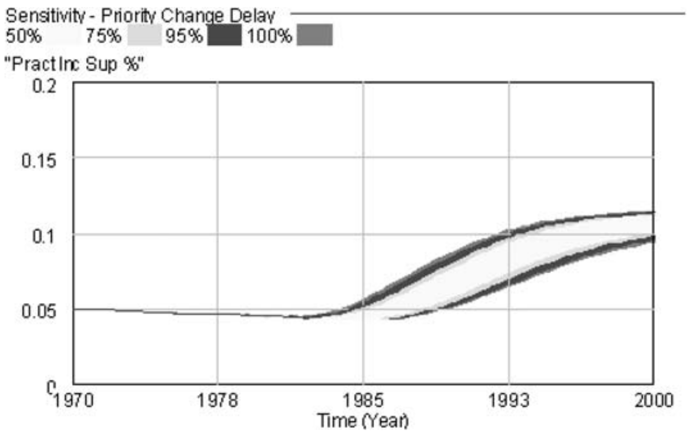

Fig. 17 Waste % to incineration—sensitivity to priority change delay

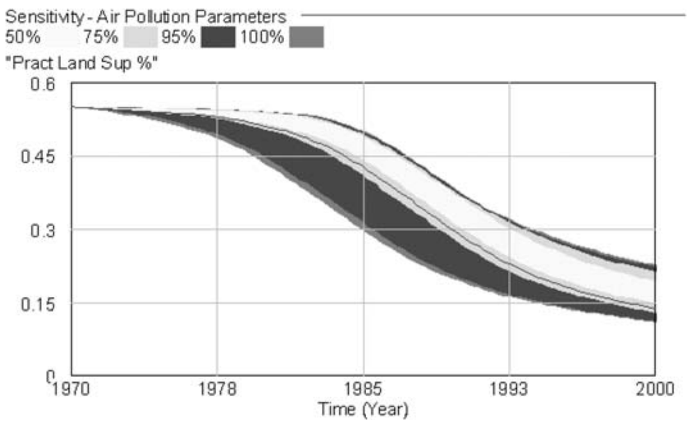

Fig. 18 Waste % to landfilling—sensitivity to air poll. performance values

5 Lessons learned from the modelling study

The Dutch waste management transition case served as an example for elucidating the feedback-centered conceptual model of transitions having actors—as socialized elements with preferences, objectives and decisions—at the core.

Three aspects of the discussed model deserves to be highlighted. The model explicitly treats actors as the driver of change in the system via the decisions they make. Secondly, the model integrates the two sides of the societal transitions (i.e. technological/physical and social) via covering both dynamics of actors perceptions and value structures, and dynamics of the infrastructure and improvement of available options. Finally, the model incorporates the feedback between the functioning of the societal system and its environment. So it closes the feedback loop between the aggregate consequences of the system's mode of functioning, and the internal dynamics of the system (i.e. preferences of the actors). The latter kind of change is generally

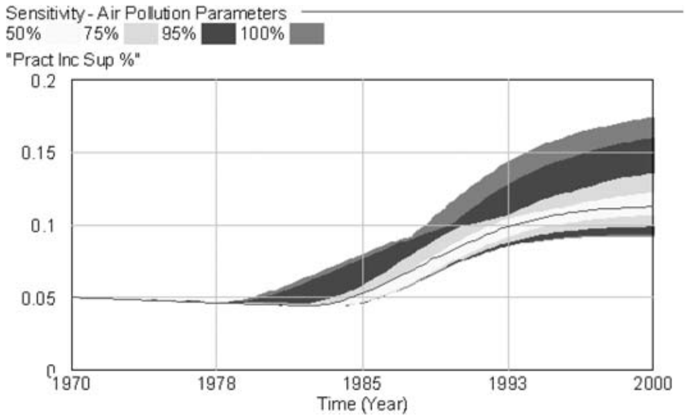

Fig. 19 Waste % to incineration—sensitivity to air poll. performance values

stimulated via exogenous signals in most of the transition models, rather than as endogenous as it has been done in this case.

The model enabled to establish the linkage between different aspects of the system and observed dynamics. Specifically, the initiation of the transition process seems to be triggered by the sense of urgency driven by the land pollution issues. The delay in the perception of the environmental consequences of landfilling yields some sort of overshooting the sustainable limits, which in turn caused the problems leading to a fast shift to the alternatives rather than slow introduction of them. Another delay in the system seems to be influential during the take-off phase of the incineration. This option reaches a significant share until the actual environmental performance becomes known by the actors in the system. The realization of the air pollution impact seems to prevent the further increase in the share of the option. However, the endogenous technological development loop seems to prevent the backlash and decrease in the share of the incineration option. The coupling of these two system aspects (i.e. the delay in the perception of the actual properties of an option, and the technological improvement mechanisms leading to success-to-successful type of consequences) reveal how an inferior option can take-off and obtain a significant share in a socio-technical system. Finally, the model also reveals how a domino effect may take place in the presence of interrelated actors having differing objectives and perspectives in the system.

To sum up, the designed model of the waste management transition case performed well in reproducing the main characteristics of the historical developments, while providing the opportunity to reveal the structural mechanisms leading to such behavior. Hence, the model stands as a promising platform that can be exploited in order to develop a better understanding of the dynamic consequences of the discussed web of feedback interactions.

6 Discussion and conclusions

The development and the interpretation of the model in this study is mainly intended to explore the SD approach when studying a large scale societal change, namely a transition. This section intends to discuss some issues regarding the application of the SD approach that resulted from this exploration process, as well as the ones recognized by the authors during their former experience with the approach.

Considering the model presented in this article, one of the first points that deserves discussion is the level of aggregation used. For example a single model actor represents the set of municipalities that are related to the modeled transition, which explicitly means that it is the "average" behavior of the municipalities that matter in the long run according to the model assumptions. The apparent drawback of such an assumption is the loss of heterogeneity and any complex dynamics that may result from the heterogeneous responses of the individual municipalities. This aggregation issue is not specific to our model, but it is a general criticism towards SD. However, there is also an important gain in such aggregations as long as the loss of information due to aggregation can be assumed not to alter long term dynamics seriously, and this loss is taken into account when interpreting the model output. Fundamentally, modeling is about reducing the complexity of the real world system to a manageable level for a researcher, and aggregation is one way of simplification. In theory it would have been possible to introduce the municipalities as separate actors in the model with all their diversity, but that would make the model almost intractable, thus it would be much harder to understand the link between the system structure and the observed dynamics. A related trade-off is the one between the model boundary and the level of detail (e.g. aggregation level) in the model. By keeping the aggregation level high, it is possible to extend the model boundary to include important slow feedback loops into the model, and still keep the model simple enough to be comprehendible. Regarding this trade-off, SD stands in favor of keeping the boundary wide enough, instead of having a very fine-grained depiction of the system.

Another point of discussion is also related to the level of aggregation used. Sticking to the high aggregation level, the researcher switches to a more conceptual world where he/she starts to think about the relationships between, for example, average income level and infant mortality, rather than more atomic relationships like hours of work and weekly income. Usually it may be possible to formulate such high level interaction by using existing theories and/or empirical data. Although it was not the case in the waste management transition model, there may also be cases where such a formulation will not be straight forward, and it will be prone to doubt and criticism. This is one of the points where SD in general attracts criticism especially from the agent-based modeling community. In the recent years, proposals have been put forward to overcome this shortcoming, which includes hybrid models (i.e. combination of agent-based and SD models). For example one of such propositions discussed is the real time coupling of an agent-based model to substitute such a hard-to-formulate interaction between two aggregate level variables (Yücel and Chiong Meza 2007), as presented in Fig. 20.

One of the biggest challenges in modeling the waste management case was the amount of soft variables included in the system of concern, and the difficulties in

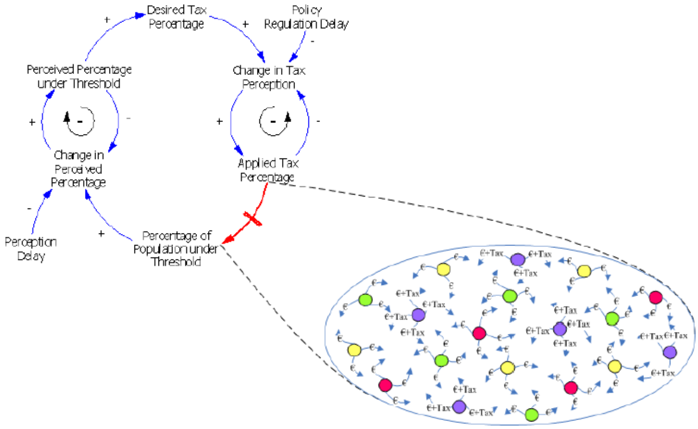

Fig. 20 Coupling of system dynamics and agent-based models

integrating them to the model as well as quantifying them. Attempting to represent behaviour of the actors who act according to the soft (i.e. hard or impossible to measure) variables like importance, priority, preference, etc. brought about the challenge of quantifying them. Considering the significance of the social components in transitions, any attempt to study these phenomena with quantitative approaches will face such a challenge. One way to deal with the issue could be sticking to the quantifiable space and ignore the soft variables, which is a very common practice. However, such a way would mean omitting these variables known to be influential, and this will probably lead to different conclusions than representing them with an error margin. Some effort was therefore devoted to quantify such soft variables. The used approach was mainly based on quantifying these variables based on a reference point. For example, importance of air pollution is selected to be reference at $t = 0$, and its value is set to be 1. Based on the qualitative data like "being more important", or "being less important", other importance variables are initialized using this reference. As a result it was possible to attribute some values to these variables that are meaningless by themselves, but have an information value during comparisons to be made with other variables of the same type. Such a model initialization significantly decreases the predictive value of the models, and increases the need for extensive sensitivity analysis to see the impact of changes in these parameters on the system behavior. In a more comprehensive transition study, it may be possible to identify some measurable indicators that may be used as representative of such soft variables.

Since the SD models, including the one discussed above, rely on ordinary differential equations they are both continuous-in-time (i.e. no discrete events are represented in the model) and continuous-in-space (i.e. variables in the model can take values in a continuous space) models. That has direct consequences in the way actors in the model behave and interact; it is not possible to have any actor instantaneously shifting to another state discretely, and interactions between actors take place in the form of continuous information flows. The approach used therefore constrains the researcher in terms of actions and interactions that can be included in the model. That might constitute a serious shortcoming in cases where discrete state shifts are crucial.

However, the very nature of transitions, conceptualized as continuous processes, fit perfectly such a continuous representation. Transitions are long term processes (e.g. 25–30 years); hence, instantaneous discrete actions or changes lose their significance in such a time frame. Additionally, since this is a matter of deep rooted regimes transforming, a continuous and smooth change dynamics may be a better representation than discrete switches in the system state.

It is important to mention that SD is a quantitative approach suitable for dealing with transitions since it has a growing toolbox that assists the researcher at various stages of the process. These include conceptualization tools (Coyle 2000), standardized methods for model validation (Barlas 1996; Forrester and Senge 1980), and formal analytical methods for identifying the influential feedback loops at any instance of a simulation run (Guneralp 2006; Kampmann and Oliva 2006; Oliva 2004). Since the focus of this paper is on the applicability of SD for analyzing transitions, information about the use of those tools during the modeling process and model use were excluded from the content.

To sum up, this paper addressed and assessed the feedback-centered perspective of SD as an approach for designing a quantitative model suitable for studying a chosen transition case while having in mind the need for understanding the underlying mechanisms of transitions.

SD is not only evaluated as a modeling technique but also as an approach for understanding complex dynamic behavior. Therefore, the replication of the system behavior, or simulation runs representing alternative scenarios are not the only outcome of a SD study. As it has been briefly demonstrated in the behavior description section, linking the observed behavior to the underlying feedback structure is another important and fundamental aspect of the approach. It is however important to consider that the plausibility of such task depends on the size of the model, which is dependent on the aggregation level chosen by the researcher.

Considering the lessons learned about the approach in general and the waste transition case in specific, SD seems to provide a fruitful perspective in understanding the complexity of the transition dynamics, especially allowing the researcher to understand how slow and fast feedbacks in the system interact and what kind of impact do time-delays in the system has on the overall dynamics. However, considering the defining characteristics of the approach (i.e. aggregate system depiction, epistemologically being closer to structuralist view, etc.) it will be erroneous to assume that this perspective alone provides enough insight about the transition processes in every aspect. It is evident that these complex processes demand a combination of approaches for understanding different aspects of them.

References

Barlas Y (1996) Formal aspects of model validity and validation in system dynamics. Syst Dyn Rev 12(3):183–210

Barlas Y, Kanar K (1999) A dynamic pattern-oriented test for model validation. In: Proceedings of 4th systems science European congress, Valencia, 1999. http://www.ie.boun.edu.tr/~ybarlas/BarlasKorhan99.pdf
Berkhout F, Smith A, Stirling A (2004) Socio-technological regimes and transition contexts, chap 3. System innovation and the transition to sustainability: theory, evidence and policy. Edward Elgar, Cheltenham Glos
Coleman J (1990) Foundations of social theory. Belknap Press of Harvard University Press, Cambridge
Coyle G (2000) Qualitative and quantitative modelling in system dynamics: some research questions. Syst Dyn Rev 16(3):225–244
Fiddaman T (1997) Feedback complexity in integrated climate-economy models. PhD thesis, Alfred P. Sloan School of Management, Massachusetts Institute of Technology
Forrester J (1961) Industrial dynamics. MIT Press, Cambridge
Forrester J (1969) Urban dynamics. MIT Press, Cambridge
Forrester J, Senge P (1980) Tests for building confidence in system dynamics models. System dynamics. North-Holland, Amsterdam, pp 209–228
Geels F (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study. Res Policy 31:1257–1274
Geels F (2005a) Co-evolution of technology and society: the transition in water supply and personal hygiene in the Netherlands (1850–1930)—a case study in multi-level perspective. Technol Soc 27:363–397
Geels F (2005b) The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles. Technol Anal Strateg Manag 17(4):445–476
Geels F, Schot J (2007) Typology of sociotechnical transition pathways. Res Policy 36:399–417
Guneralp B (2006) Towards coherent loop dominance analysis: progress in eigenvalue elasticity analysis. Syst Dyn Rev 22(3):263–289
Homer J (1987) A diffusion model with application to evolving medical technologies. Technol Forecast Soc Change 31(3):197–218
Kampmann C, Oliva R (2006) Loop eigenvalue elasticity analysis: three case studies. Syst Dyn Rev 22(2):141–162
Keeney R, Gregory R (2005) Selecting attributes to measure the achievement of objectives. Oper Res 53(1):1–11
Keeney R, Raiffa H (1993) Decisions with multiple objectives: preferences and value tradeoffs. Cambridge University Press, Cambridge
Loorbach D (2007) Transition management: new mode of governance for sustainable development. PhD thesis, Erasmus University, Rotterdam
Mahajan V, Peterson R (1985) Models for innovation diffusion. Quantitative applications in the social sciences. Sage, Thousand Oaks
Mahajan V, Muller E, Wind Y (eds) (2000) New-product diffusion models. Kluwer Academic, Dordrecht
Meadows D, Meadows D, Randers J, Behrens W (1972) The limits to growth. Potomac Associates, New York
Oliva R (2004) Model structure analysis through graph theory: partition heuristics and feedback structure decomposition. Syst Dyn Rev 20(4):313–336
Randers J (1980) Guidelines for model conceptualization. In: Randers J (ed) Elements of the system dynamics method. Productivity Press, Cambridge
Richardson G, Pugh A (1961) Introduction to system dynamics modelling with DYNAMO. MIT Press, Cambridge
Richardson GP (1991) Feedback thought in social science and systems theory. University of Pennsylvania Press, Philadelphia
Rogers E (1983) Diffusion of innovations, 3rd edn. Cambridge University Press, Cambridge
Rotmans J (2005) Societal innovation: between dream and reality lies complexity. Erasmus University, Rotterdam
Rotmans J, Kemp R, Asselt M (2001) More evolution than revolution: transition management in public policy. Foresight 3(1):15–31
Schade B, Schade W (2005) Assessment of environmentally sustainable transport scenarios by a backcasting approach with escot. In: Proceedings of the 23th International conference of the system dynamics society, Boston, 2005
Sterman J (1981) The energy transition and the economy: a system dynamics approach. PhD thesis, Alfred P. Sloan School of Management, Massachusetts Institute of Technology

Sterman J (1994) Learning in and about complex systems. Syst Dyn Rev 10(1):291–330
Sterman J (2000) Business dynamics: systems thinking and modeling for a complex world. Irwin/McGraw-Hill, Boston
Struben J, Sterman J (2008) Transition challenges for alternative fuel vehicle and transportation systems. Environment and planning B: planning and design advance online publication
Unruh GC (2000) Understanding carbon lock-in. Energy Policy 28:817–830
Unruh GC (2002) Escaping carbon lock-in. Energy Policy 30:317–325
van der Brugge R, Rotmans J, Loorbach D (2005) The transition in Dutch water management. Reg Environ Change 5:164–176
Yücel G, Barlas Y (2007) Pattern-based system design/optimization. In: Sterman J, Oliva R (eds) Proceedings of the 25th international conference of the system dynamics society, Boston, 2007. http://www.systemdynamics.org/conferences/2007/proceed/index.htm
Yücel G, Chiong Meza CM (2007) Benefiting from the other: proposals on incorporating agent based and system dynamics approaches. In: Amblard F (ed) Proceedings of the 4th conference of the European social simulation association, Toulouse, 2007. http://essa2007.free.fr/ESSA2007Proceedings.pdf

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