Transition can be characterized as long-term structural changes in the societal systems, through which the way these systems function change significantly. Both the scope and extent of change, and the nature of the societal systems make transition processes a complex dynamic phenomena to understand.

This study explores both methodological and conceptual issues in order to contribute to the ways transitions are analyzed. On the methodological frontier, the book investigates different forms of simulation-supported analysis. On the conceptual frontier, the study focuses on structural and behavioral similarities among socio-technical systems in order to develop a general modelling framework that can serve as a conceptual basis for simulation-supported analyses. Additional to introducing the developed framework, i.e. the actor-option framework, the book also presents a set of modelling studies that are based on it.
Analyzing Transition Dynamics
The Actor-option Framework for Modelling Socio-technical Systems

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Delft University of Technology
2010
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The Actor-option Framework for Modelling Socio-technical Systems

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# Table of Contents

## Chapter 1. Introduction

1.1. Emergence of transitions as a policy issue ........................................ 1
1.2. Characterizing transitions: what is a transition? .................................. 3
1.3. Overview of the transition studies field ............................................. 5
1.4. Looking ahead: promising directions for analytical transition studies .... 15
1.5. The scope and objectives of this study .............................................. 20
1.6. Organization of the dissertation ..................................................... 23

## PART I. Simulation-supported Analysis in Transition Studies

### Chapter 2. Simulation-supported Analysis

2.1. Simulation and simulation models .................................................. 27
2.2. Analyzing transitions through simulation ...................................... 28
2.3. Different uses of modelling and simulation in the transition studies field 33
2.4. Challenges in simulation-supported analyses of transition dynamics .... 38
2.5. Conclusions .................................................................................. 41

## PART II. The Actor-Option Framework

### Chapter 3. Different Approaches to Modelling Transitions

3.1. Introduction .................................................................................. 45
3.2. General overview of modelling paradigms ...................................... 45
3.3. Categorizing conceptual perspectives in simulation modelling ......... 47
3.4. System dynamics (SD) .................................................................. 48
3.5. Agent-based Modelling (ABM) ..................................................... 50
3.6. Conclusions .................................................................................. 53

### Chapter 4. Building Blocks of the Framework

4.1. Introduction .................................................................................. 61
4.2. Options ....................................................................................... 62
4.3. Actors .......................................................................................... 64
4.4. Interaction of the actors and options ............................................. 67
4.5. Conclusions .................................................................................. 73
Chapter 12. Conclusions and Reflections

12.1. Overview of the overall objectives of the study

12.2. Simulation-supported analysis of transition dynamics

12.3. The actor-option framework

12.4. Investigating the actor-option framework through application

12.5. General reflections and prospective directions of research

Bibliography

Appendix A. The WasteTrans Model

Appendix B. The NavalTrans Model

Appendix C. The ElectTrans Model

Summary

Samenvatting

Acknowledgements

About the Author
Introduction

1.1. Emergence of transitions as a policy issue

'Sustainability', as a concept, has established an important place in the policy-making domain during the last couple of decades. The rise of the concept started around the 1960s, and has been continuing since then in parallel to the increasing publicity of large-scale global, and mainly anthropogenic, problems¹. The accumulation of synthetic agricultural chemicals (e.g. DDT) along food chains (Dunlap 1981), the deterioration of the ozone layer in the atmosphere (Solomon et al. 1986), and global climate change (IPCC 2007) are the most prominent examples of such problems. Especially, a set of publications that became quite popular in 1960s and 1970s, including 'Silent Spring' (Carson 1962) and 'Limits to Growth' (Meadows et al. 1972) played an important role in increasing concerns regarding sustainability of the growth-oriented human activity on earth (Ehrlich 1972; Goldsmith et al. 1972). The increasing materialistic nature of lifestyles was widely questioned, and put at the loci of the sustainability discussions. Later, the concept of 'sustainable development' was formally defined² and took its permanent place in the national, as well as international policy arenas with the publication of 'Our Common Future' (Bruntland 1987), which is also widely known as the Bruntland Report.

The discussions on the issue, and the early publications that indicate potential economic, ecological and demographic catastrophes acted as the main force behind the diffusion of the sustainability concept as a normative meta-goal. The wide spread acceptance of the idea made it one of the most intensely visited topics in a wide spectrum of research fields.

Shifting to a sustainable mode of living is a meta-goal that is easy to build consensus on. However, the same cannot be claimed for depicting new and sustainable lifestyles, let alone

¹ Actually, the first concerns regarding global sustainability can be traced back to 18th century, when Thomas Malthus claimed that the pace of population growth could not be sustained due to the limits on agricultural yields needed to support that growth (Malthus 1798).
² Sustainable development is the development that meets the needs of the current generation, without compromising the needs of future generations.
seeking a consensus on them. The difficulty of specifying sustainable lifestyles (e.g. carbon-free mobility, 0-emission living environments) makes the quest for designing such lifestyles an important and widely discussed research topic. This has been supplemented by intensive innovative activity (e.g. scientific research, R&D activity) aiming to develop technologies and artefacts (e.g. fuel cells, hydrogen-fuelled cars) that can make those sustainable lifestyles possible. However, it became apparent that an important piece of the puzzle was missing: how to shift to these alternative lifestyles.

The problems that raise sustainability concerns can mostly be categorized as ‘wicked problems’ (Rittel and Webber 1973) or as ‘persistent problems’ (Loorbach 2007; Rotmans 2005): they are difficult to solve because of incomplete, contradictory and changing requirements that are often difficult to recognize; and, because of complex interdependencies, the effort to solve one aspect of such a problem may reveal or create others. Both of these defining characteristics of wicked problems can be attributed to the nature of the corresponding societal systems, which are large-scale systems and possess dynamic complexity rooted in their structure. To be more specific, the sustainability problems are about the way constituents of the related societal systems interact, and the way these systems function as a whole. These systems incorporate social, environmental, economic and technological aspects interacting with each other via a multiplicity of intertwined relations. These aspects (constituents and/or subsystems) are dynamic and adaptive in nature; i.e. they change over time, and their temporal development can change direction and pace due to changes in the environmental conditions. Moreover, contingencies (e.g. social, technological) combined with the aforementioned dynamic complexity play an important role in altering the development of these systems. It is clear that governing these systems towards a predefined state is extremely difficult, if not impossible, and demands approaches that go beyond the standard portfolio of policy interventions. It is important to clarify that the difficulty mentioned at this point is totally independent of another extremely challenging task, which is the identification of a desirable state or mode of behaviour that can be accepted as sustainable by different stakeholders of the issue.

Due to the complexity that is a consequence of the reactive and adaptive nature of the societal systems, simple policy interventions with the aim of changing these systems to a desirable state may have no permanent impact. Moreover, such interventions may even trigger unexpected and counterintuitive reactions in the system, which can result in the system ending up at a state totally different from the one expected. This aspect of the sustainability problem, i.e. the process of system transitions to sustainable configurations, constitutes the main issue of concern in transition studies; a relatively young field of interdisciplinary research on system transitions (Geels 2005b; Grin et al. 2010; Rotmans et al. 2001).

The ultimate goal of the transition studies field is to develop novel policy interventions and governance approaches that enable steering comprehensive system-wide change processes needed for transitions to sustainable system configurations. However, as highlighted above, the internal dynamics of societal systems can be even too complex to understand, let alone controlling and steering them. This dynamic complexity constitutes an important research niche within transition studies, since the understanding to be developed about regularities related to the dynamics of systems in transition (e.g. drivers, mechanisms, conditions, patterns, etc.) is an important pre-condition for reaching the ultimate goal of the transition studies field. In the absence of such an understanding about the internal dynamics of these
systems, the efforts for developing transition policies and governance models could resemble groping in the dark.

The research that is discussed in this dissertation resides in the research niche of transition dynamics, which primarily focuses on understanding the aforementioned complex dynamics of transitional changes. Before going into the main research objectives, and the issues that motivate this research, the following sections provide an overview of the key concepts and issues in the transitions field, and the state-of-the-art regarding them. In the following section, the transition concept is discussed in further detail. Following that, Section 1.3 focuses on the core topic of this study, namely transition dynamics, and reviews the current state-of-the-art. Section 1.4 lays down some gaps and promising directions for development in the current state of the studies on transition dynamics. The main objectives and the scope of this study are summarized in the last section of the chapter, namely in Section 1.5. Finally, Section 1.6 summarizes the organization of the dissertation.

1.2. Characterizing transitions: what is a transition?

The word transition literally refers to ‘a movement, development, or evolution from one form, stage, or style to another’ (Merriam-Webster 2010). Along the line of developments that led to the emergence of the transitions field, the word ‘transition’ acquired a field-specific characterization.

**Box 1. Various transition definitions provided in transition studies**

- “A transition can be defined as a gradual, continuous process of structural change within a society or culture.” (Rotmans, Kemp et al. 2001)
- “Technological transitions are defined as major technological transformations in the way societal functions such as transportation, communication, housing, feeding are fulfilled.” (Geels 2002a)
- “A transition denotes a long-term change in an encompassing system that serves a basic societal function (e.g. food production, mobility, energy supply, communication, etc.)” (Elzen and Wieczorek 2005)
- “A transition is a structural societal change that is a result of economic, cultural, technological, institutional, as well as environmental developments, which both influence and strengthen each other.” (Rotmans 2005)
- “[A societal transition is] a fundamental change in the structures, cultures and practices of a societal system, profoundly altering the way it functions.” (de Haan 2010)
- “A transition is understood as having occurred when the societal system functions in a different way for which the composition of the societal system had to change fundamentally.” (Frantzeskaki and de Haan 2009)

As a natural consequence of the heterogeneity in the backgrounds and the perspectives among transition scholars, the definitions used for a transition demonstrate variety. The selection of transition definitions given in Box 1 provides a sample of such variety. Despite the nuances among the used definitions, a set of key aspects is common to most of the transition processes characterized in those definitions. Although it is likely that the variety in the transition definitions will prevail in the field, such key aspects appear to be the basics of the process agreed upon by the majority of the scholars working on the subject. Therefore, it is important...
to go through those basics before explicitly discussing what is considered as a transition in this dissertation. The three basics of a transition characterization can be summarized by the following three questions:

i. **What is going through change?**

The domain of change in transitions is a human-technology-ecology system, in the broadest sense. These are systems that incorporate interacting sub-systems, such as social, economical, institutional, technological, infrastructural, and ecological systems, that are also internally dynamic in nature. The social sub-systems are always a prominent piece of these systems that are the subject of interest in transition studies. In other words, non-social systems, such as purely technological or ecological systems, are not of any interest in the field. Therefore, the domain of transition studies is societal systems, in general. In cases where another sub-system plays an equally important role in the dynamics of the overall system, the domains of transition can be defined more specifically, like socio-technical or socio-ecological systems.

ii. **Which aspects of the societal system are changing?**

A societal system can change in various aspects, but not all these changes are of interest in transition studies. Going back to the line of developments that led to the emergence of the field, it is a set of problems about the way these societal systems function that inspired the field. The concept of *functioning* (i.e. the way a system functions) plays an important role in the characterization of a transition, as can be seen also in the definitions provided in Box 1. The societal systems subject to the transition studies are directly related to a societal need, such as food, health, mobility, energy, and water. The functioning of the societal system, simply put, refers to the internal configuration of the system’s elements and the way these elements interact in the context of the societal need associated with the system. This functioning (i.e. the way the societal need is fulfilled within/via the societal system) is the aspect of the societal systems that is changing in a transition.

iii. **What is the extent of change in the way the societal system functions?**

The final aspect that characterizes a transition is the extent, or the scope, of the change in the way societal system functions. A change is qualified as a transition when it is possible to claim that the change in the system’s functioning is significant and permanent. Significance and permanence are both relative notions in this context. Although it is not possible to give clear-cut specifications for them, some elaboration may clarify what they mean in this text. A societal system can be characterized via a multiplicity of dimensions; for example, a mobility system can be characterized via its spatial coverage, average distance travelled per person, the dominant mode of transport, distribution of fuel used, variety of the travel options, reliability of the overall system, risk of accidents, or governance of the system. A transition generally relates mainly to a subset of such dimensions. In that respect, a significant change refers to shifting to an alternative way of system functioning that is characterized very differently from the formerly dominant one along this subset of dimensions. It is difficult to talk about an absolute permanence, and the relative permanence brings about the question; how long is permanent? The permanence mentioned here is more related to the irreversibility of the process. In the face of a fuel shortage, people may significantly change the way they travel to work. However, as soon as the shortage is over, the old way of doing things will most likely
appear again. Despite being significant, this would not qualify as a transitional change since it is not permanent, or since it is easily reversible. This short elaboration should help to clarify what is meant by these relative concepts. However, the subjectivity in the nature of these concepts is unavoidable (e.g. is 50% reduction in fossil fuel use significant?), and this makes the transition an intrinsically subjective concept to define.

When the three aspects discussed above are combined, a transition can be defined, in general, as a significant and permanent change in the way a societal system functions with respect to the fulfilment of a societal need.

1.3. Overview of the transition studies field

So far in this chapter, the term ‘transition studies’ has been used to refer to the totality of the studies related to transitions. However, it is beneficial to distinguish the clusters within this general group in order to clarify the position of this particular research within the transitions field. Two fundamentally different clusters can be identified at the first glance; theoretical and applied transition studies. The theoretical transition studies focus primarily on the development of a general understanding of the transition processes, and ways of altering the dynamics of these processes (e.g. Berkhout et al. 2004; Elzen and Wieczorek 2005; Rotmans, Kemp et al. 2001). The applied transition studies build on top of the findings of the former cluster, and focus on particular transition problems by using the concepts and methods developed as a result of the theoretical transition studies (e.g. Holtz 2008; van den Bosch et al. 2005). This research primarily belongs to the first cluster, as will be clear when discussing the main objectives of the research in the following sections.

It is also possible to distinguish two different sub-groups within the theoretical transition studies; process-oriented and analytical transition studies. The process-oriented studies primarily focus on the design of processes and approaches that can be used in steering dynamics of transitions. In other words, they focus on policy intervention processes for realizing desired transitions. The most prominent examples of this type of research are on the transition management (e.g. Loorbach 2007), strategic niche management (e.g. Kemp et al. 1998), and reflexive governance (e.g. Voß et al. 2006) approaches. The analytical transition studies, on the other hand, deal with the analysis of the societal systems and their change dynamics. This covers both developing analytic approaches, and utilization of these approaches to contribute to a developing ‘transition theory’. This research is a typical example of the latter sub-group of the theoretical transition studies, i.e. analytical transition studies. In that respect, a brief overview of the state-of-the-art in this particular strand of transition studies is given below.

The review consists of three sub-sections. The first sub-section discusses mainly the early studies in the field that frame the research problems about transitions, and specifically about transition dynamics. The second sub-section focuses on the concepts and the conceptual frames that are proposed to structure the analysis on transition dynamics. The third sub-section is about the state-of-the-art in descriptive and explanatory analysis of transition processes. It is worthwhile to note that, although it is not necessarily always the case, there is a significant correspondence with this layout of the sub-sections, and the chronological development of the analytical transition studies.
Chapter 1

Framing the research problem

One major type of contribution of the publications in the field, especially the earlier ones, is related to laying down the transition problématique; framing the problem and emphasizing the major aspects of the transition process that are of interest. This group of transition studies mainly focuses on what happens in a transition, and what needs to be understood and explained.

i. Different manifestations of change

The simplified depiction of plausible societal change paths discussed by Rotmans (2005) can be considered an early typology of change (Figure 1.1). The set of paths discussed by Rotmans (ibid.), and later by van der Brugge (2009) following Rotmans, mainly resembles typical (innovation) diffusion dynamics, and includes (successful) transition, lock-in, backlash, and system breakdown paths, as the authors name them. This ‘typology’ of change serves a fundamental function in raising the question that lie at the foundations of the research on transition dynamics; how do these paths come about, and why a certain system follows a particular behaviour path, while another similar system goes through a totally different one? Despite being very powerful as a high-level discussion ground and communication aid, such a depiction of different change patterns is somewhat simplified (e.g. change is depicted as a one dimensional process; up or down), and not rich enough for analyses into transition dynamics.

ii. Multi-phase nature of transitions

Another widely mentioned concept in the analytical transition studies is the multi-phase nature of the transitions. Rotmans et al. (2001) postulate that transitions manifest themselves in a sequence of phases that differ with respect to the pace of change in the system. The four phases, which are mainly based on the simplified depiction of a transition as a S-curve (see Figure 1.1 and related discussion above), consist of pre-development, take-off, acceleration, and stabilization phases (ibid.) (Figure 1.2). The multi-phase nature of the transitions constitutes one of the four major hypotheses that are laid down by Rotmans as the foundations of the evolving transition theory (Rotmans 2005). As the typology of change dynamics, the multi-phase concept is simplistic, and abstract. These aspects make it a key concept for broad discussions on transitions. Moreover, the multi-phase hypothesis provides an important perspective and raises some fundamental questions: first of all, it is a concrete statement about the non-linear nature of the pattern of change (i.e. alternating slow and fast dynamics). Secondly, it raises the question of whether the pattern depicted by the S-curve is common to all transitions, or not. In other words, are there other multi-phase transition
patterns? Finally, it points out a research niche where the objective is to reveal the factors underlying the alternation of the pace of change during a transition process.

b. Framing the analysis
Besides concepts that mainly define the problem of concern, there are also concepts and perspectives that are proposed to guide analyses. In this section, we discuss the most prominent examples of such concepts and perspectives.

i. Multi-level perspective
One of the most prominent conceptual perspectives in the transitions field is the multi-level perspective (MLP). Some of the basic concepts closely associated with MLP are initially discussed by Kemp (1994). Building on these concepts, the multiple layers of analysis are explicitly introduced by Rip and Kemp (1998) in their work that mainly focuses on technological development. Later, the perspective is slightly enriched and re-interpreted by Geels (2002a; 2002b; 2005a) in order to apply the perspective in analyzing transition dynamics, which encompasses a broader change than just a technological one.

Since the appearance of MLP, the perspective has been going through a conceptual evolution, and it has been interpreted differently by various scholars in the field. Despite such interpretational variety, the basic notions are shared by almost all: as the name implies, MLP prescribes to frame the analysis of transition dynamics in multiple distinct levels; namely the micro, meso, and macro levels. According to MLP, dynamics of transitions are analyzed primarily based on the dynamics within and among these levels. The level of novelties (e.g. technology, practice, idea) is labelled as the micro level. The dominant/usual way of doing the things in the context of the societal function of concern is associated with the meso level. Finally, the contextual factors and developments that are independent of the micro and meso level dynamics within the time frame of the analysis are located in the macro level.

Three concepts closely related to the aforementioned levels are the niche, regime, and landscape concepts. Unfortunately, it is not possible to talk about commonly used and precise
definitions for these three concepts. In general, the *niche* corresponds either to a social field (e.g. markets, company networks, etc.) in which novelties are accepted and nurtured (e.g. Schot and Geels 2007), or to a social, institutional and technological whole around a novel way of fulfilling the societal function (e.g. Loorbach 2007). Similar differences also exist for the *regime* concept. However, in general, the *regime* is associated with the structure of the societal system associated with the dominant way of fulfilling the societal function prior to a transition. The *landscape*, as the name implies, is used to cover the hard-to-change context (e.g. technological, material, ecological, cultural, economical, etc.) in which the *regimes* and *niches* are embedded. The *landscape* has its own -usually slow- internal dynamics that are not influenced by the *regime* or *niche* dynamics, and it sets the boundaries and constitutes the backdrop for the developments related to the latter two. As should be apparent from the descriptions, there is a one-to-one association between the *micro*, *meso* and *macro* levels, and the *niche*, *regime* and *landscape* concepts, respectively. Due to their close association with the levels, these concepts are also used to label the levels; e.g. *niche-level* for the *micro level*.

An important aspect of the levels that requires explicit clarification is their non-ontological nature: they are just conceptually constructed levels, which are proposed to serve as pieces of a guiding framework to examine transition dynamics. In that respect, these levels can only be recognized posterior to the specification of the subject (e.g. mobility, energy) and the aggregation level (e.g. regional, national) of the transition to be analyzed (Geels and Schot 2007). The concept of ‘level’ suggests an ontological aggregation or hierarchical relation among the levels of MLP, which is not the case. In other words, these levels can easily be interpreted as different domains of change. MLP proposes analyzing the changes within these three different domains, and the interactions between them for studying transitions.

Parallel to the wide spread adoption of MLP in almost all strands of the transition studies field, the perspective has also attracted criticism regarding, for example, the descriptive nature of the perspective, unsystematic nature of its development process, teleological stance dominant in the historical narratives using MLP, and the extent of empirical applicability of the levels (Berkhout, Smith et al. 2004; Genus and Coles 2008; Markard and Truffer 2008; Smith et al. 2005; Smith et al. 2010). The concerns raised in such criticisms are relevant, and they point out important opportunities for further enrichment of the perspective. However, even in its current form, MLP provides a frame of analysis for the researcher about what to consider while attempting to understand transition dynamics. Although it does not provide specific clues about the processes underlying transition dynamics, it points towards three domains of change that should be kept in the locus of an analysis.

Despite the wide spread usage of the *regime* concept in general discussions, little has been done on specifying what really constitutes a *regime*. In other words, when the MLP is to be applied in a policy analysis practice, it is not very clear where to draw the boundaries for the case-specific *regime*. Holtz points this out as a void in the current state of the transition studies field, and as an especially important one that is holding back the effective utilization of MLP in policy studies (Holtz 2009; Holtz et al. 2008). In that respect, Holtz proposes an approach for structuring the process of identifying the major elements of a *regime*, as well as the nature of their interactions. This framework can be seen as an important attempt to go a bit deeper into the specification of the *regime* concept, and establish the link between the conceptual foundations of the transition studies, and empirical policy analysis work.
Schot and Geels (2007) propose four different types of *niches* in their review on the concept of *niches* in the evolutionary theories. Although this is not the primary objective, it can also be evaluated as a contribution towards further specification of the *niche* concept used heavily within MLP. The four *niche* types proposed by Schot and Geels (ibid.) are as follows:

- **Regime internal market niche:** A niche that features high stability and low protection/isolation from the prevailing socio-technical regime
- **Regime external market niche:** A niche that builds on isolation from the socio-technical regime and contains stable rules
- **Technological niche:** A niche that is isolated from the socio-technical regime and features no stability
- **Breakthrough niche:** A niche that is not isolated or protected from the socio-technical regime but does not yet contain stable rules

### ii. Functions of innovation systems

MLP provides multiple levels and related basic notions to structure analyses of transitions across cases. Another approach proposed with very similar general objectives is the *functions of innovation systems* approach (Bergek 2002; Hekkert and Negro 2009; Hekkert et al. 2007), which proposes a set of *functions* to structure analyses. The approach focuses, not on a societal system under transition, but on a particular technology and the innovation system related to this technology as the subject of analysis. In that respect, it has a different scope and viewpoint, and it mainly aims to analyze the development of a particular technology. Despite this difference, the approach still provides a useful and relevant analysis framework in the context of transition studies (e.g. Hillman et al. 2008), since the development of novelties plays an important role within the transition context.

The approach provides a list of seven major *function* classes, which can be used to map the activities taking place in an innovation system. The situation in terms of the intensity and the direction (i.e. *against* or *for* the innovation) of the activities within each *function* type provides an overview of the system, and can be used as the basis for analyzing the success or failure with respect to the particular technology. The seven functions are as follows (Hekkert, Suurs et al. 2007);

- Function 1: Entrepreneurial activities
- Function 2: Knowledge development
- Function 3: Knowledge diffusion
- Function 4: Guidance of the search
- Function 5: Market formation
- Function 6: Resource mobilization
- Function 7: Advocacy coalition

These seven functions are not isolated from each other in the context of an innovation system, but are interdependent, i.e. a success in one function may trigger a success in another function (Bergek 2002). Although this interdependency has been highlighted, the nature of such interdependencies has become a subject of interest only very recently (e.g. Negro 2007; Suurs 2009).

In summary, the *functions of innovation systems* approach provides an analytical structure, which is composed of seven functional domains to focus on, for studying the success or failure
of certain technological niches in the context of socio-technical transitions. In that respect, it can be seen as a complementary perspective to MLP.

c. Describing and explaining transition dynamics
The overall objective of the analytical transition studies is to develop a general understanding about transitional change processes. Two very important contributions towards achieving such a generic understanding are the development of general descriptions and explanations for transition dynamics. Although the terms 'description' and 'explanation' have some overlap in meaning and resemble each other, the nuance between them is very important in this particular context. Roughly, the description refers to the provision of an account of the way a transitional change took place. On the other hand, the explanation lays down the factors and processes that yield the transition to take place in that particular way. This distinction will be used in discussing the current state of the field during the following sub-sections.

There are numerous publications that discuss the dynamics of transitions within the particular context of a single case study (e.g. Belz 2004; Raven 2007; Scholz et al. 2009; Tabara and Ilhan 2008; van der Brugge et al. 2005). Despite their case-specific nature, these studies naturally contribute to the general understanding about the transition dynamics. However, none of them takes the transitions in general as their subject of inquiry, and they do not provide a comprehensive and generic account of the transition processes. Two major efforts are distinguished from these case-specific transition analyses, in this respect: the induction-based efforts of Geels and his co-authors (Geels 2002a; Geels 2002b; Geels 2005a; Geels 2005c; Geels and Kemp 2007; Geels and Schot 2007) based on historical case studies, and the deduction-based efforts of de Haan (2010). These two efforts are discussed under three sub-sections, each corresponding to a major question that needs to be answered for a comprehensive account of transition dynamics;

- **When do transitions take place?**
  This question aims to reveal the conditions, events, or other developments that trigger the chain of changes that eventually constitute a transition.

- **What happens during a transition?**
  The different manifestations of transition processes, and description of the way transitions take place

- **Why do transitions manifest themselves in specific ways?**
  This question focuses on the processes and events underlying the transition, and in some sense driving a transitional change process.

i. **When do transitions take place?**
In an early attempt to answer this question, Geels (2005b) proposes a set of circumstances that create a ‘window of opportunity’ for a transition. Although it looks like an unsystematically constructed list, the logic behind this list of circumstances is closely related to two important aspects that are visible in Geels’ analyses. One of them is the technological focus, which results in the analyses to be woven around alternative technologies competing for the dominance in the system. Secondly, there is some level of pro-niche bias in these analyses, which reveals itself in the ‘promising niche-innovation’ being the protagonist in the transition narratives and in the

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3 (to) describe: to represent or give an account of in words; to give a mental image of something experienced
4 (to) explain: to give the reason for or cause of
5 Similar to the pro-innovation bias discussed by Rogers (1983) in the context of studies on diffusion of innovations.
chosen terminology. These also influence the way Geels attempts to answer this question: as a consequence of the pro-niche bias, the answer focuses on the contextual factors that enable a niche-innovation to gain wider acceptance in the socio-technical system, or, in other words, that create a ‘window of opportunity’ for a niche innovation. Based on the historical case studies, Geels proposes a non-exhaustive set of circumstances that can “create a window of opportunity for the wide diffusion of novelties” (Geels 2005b, p. 91). These circumstances are as follows:

- External problems, such as environmental negative externalities
- Internal technical problems in the existing regime that cannot be solved by the available technology
- Changing user preferences
- Strategic and competitive games between firms that can speed up the development of the new technology
- Availability of complementary technologies for the new technology

Although this list of circumstances lacks a structure behind it and is not an exhaustive one, the relation between these circumstances and the layers of MLP is apparent: external problems are related to landscape developments that put pressure on the regime. The second and the third cases in the list correspond to internal regime developments that create a transition-friendly environment. Finally, the last two circumstances can be linked to the niche-level developments.

The second attempt to provide an answer to the aforementioned question is the conditions proposed by de Haan (2010). The link between the MLP levels and the conditions proposed by de Haan is much more apparent. The MLP levels are used as the starting point in identifying transition-triggering conditions, which constitute one of the pillars of the pillar theory (ibid.). According to de Haan, a transition is assumed to be initiated only when the ‘dominant constellation’ in the societal system, i.e. the regime, is having some problem with the way it functions. The three conditions proposed by de Haan, i.e. tension, stress and pressure, are based on the possible origins of these problems.

- **Tension:** The problems of the system in its relations with its environment, i.e. landscape, are the sources of tension between the regime and the landscape.
- **Stress:** In cases where the regime is not adequate, or is internally inconsistent with respect to the function it is associated with, stress forms within the regime.
- **Pressure:** When competitive alternatives to the regime appear in the niche-level, these novel alternatives are said to exert pressure on the regime.

Differing from the Geels’ case, this conceptualization of conditions is an outcome of a deductive process, and it also has a claim of being exhaustive; i.e. any condition that triggers a transition can be characterized as one of these three generic condition types, according to de Haan (ibid.).

**ii. What happens during a transition?**

An early example of the descriptive attempts is proposed by Geels (2002b), and is related to the narrowly defined technological transitions. In this attempt, a (technological) transition is depicted as a sequence of four phases, and these phases are distinguished based mainly
on the dominant processes going on in the system. According to this depiction, a transition starts with the emergence of a novelty (i.e. Phase 1). The second phase is characterized by the technical specialization and exploration of new functionalities taking place around the novelty. The breakthrough (i.e. wide diffusion) of the novelty marks the third phase, and the final phase covers the period during which the gradual replacement of the established regime with the novelty is observed.

When the scope of the analysis is extended from a technological to a socio-technical (or societal) transition, the proposition of having a single manifestation of transitions is questionable. In that respect, a more recent contribution of Geels and Schot (2007) introduce four stereotypical narratives (descriptions) for transitions, to which they refer to as pathways. This pathway typology is mainly based on MLP, and the different pathways are distinguished according to two aspects; the timing of the inter-level influences (e.g. whether the landscape puts pressure on the regime first, or not), and the nature of the influence (e.g. whether the influence is reinforcing, or counteracting a transition). Four main pathways are proposed in this typology:

- **Transformation**: Driven by landscape pressure, the regime transforms itself in order to adapt to the changing external conditions. No novelties at the niche level are included in the process.
- **De-alignment and re-alignment**: The regime does not have the potential (or room) to adapt to the landscape changes, and a de-alignment of the regime takes place. There is no niche-innovation ready to replace the regime. Therefore, a period of competition among promising niches-innovations ends up with one of them emerging as the dominant, and a re-alignment of a new regime around it.
- **Technological substitution**: When the regime faces the landscape pressure, there is an already competitive niche-innovation ready at the niche-level. The niche-innovation breaks through and the old regime is replaced with the new one that forms around this new niche-innovation.
- **Reconfiguration**: Some niche-level innovations are adopted in the regime to deal with some small problems. In some sense, these niche-innovations are nurtured within the regime, and later a new regime develops around these niche-innovations. In other words, a new regime grows out of the old one following the symbiotic adaption of the niche-innovations.

Besides these four types, two other types are included in the typology. The first one, i.e. reproduction, represents the no-transition case, and depicts the ongoing change in the regime level even in the absence of external pressures. The second one, i.e. sequence of transition pathways, stands more like an ‘others’ class rather than a well-specified narrative as the aforementioned four.

Parallel to the aforementioned efforts on describing a set of stereotypical transitions, de Haan (2010) proposes a theoretical approach to systematically describe transitions in general, and

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6 This 4-phase depiction of Geels resembles the multi-phase hypothesis of Rotmans discussed before. However, the phases of Geels focus more on the processes taking place (e.g. whether novelty starts diffusing at a wider scale, or not), rather than the system level consequences of these processes (e.g. whether change speeds up, or not) as was the case in the phases of Rotmans. Therefore, this 4-phase depiction is discussed in this section.

7 Geels and Schot frequently use the term ‘pressure’ in their discussions. However, they do not specifically refer to the pressure concept of de Haan. The word is in italic fonts when it refers to the pressure condition of de Haan.
he supplements the approach with a corresponding typology of transitions. Building on the basic notions of MLP, the regime and niches are the main constellations, whose dynamics determine the way a transition unfolds. Departing from this position, de Haan focuses on identifying general change processes that can be observed regarding these constellations. This leads to the identification of three patterns of change (i.e. the second pillar of the pillar theory), of which first two are related to the niches, and the third one is about the regime; 

- **Empowerment**: “A new constellation emerges or an existing one gains power from within the societal system.” (ibid.)
- **Re-constellation**: “A new constellation emerges, or an existing one gains power from outside the societal system.” (ibid.)
- **Adaptation**: “A constellation incorporates alternative functioning.” (ibid.)

These three patterns are proposed as modular dynamic units that can be combined to create a chain of patterns, or a path (i.e. the third and the last pillar of the pillar theory). These paths constitute narratives for transition processes. Using the three patterns mentioned above, the analyst can re-construct a transition story in a systematic way. There are two fundamental assumptions made by de Haan in making such an assertion; any transition story can be told using these three patterns, and a transition path as a whole can be described as a chain of patterns.

The patterns are generic descriptive elements, which can be used in analyzing specific transition cases, or transitions in general. According to the two fundamental assumptions given above, each transition is a path, and can be depicted by combining a set of patterns in an appropriate order to form a chain. As a result, it is apparent that infinite number of different transition paths can be created using different number of patterns, and by ordering them differently. However, de Haan proposes a sort of summary for this infinite variety with a general typology of transition paths. Two dimensions are used to differentiate the path types in this typology: the first dimension is related to the ‘dominant pattern over the course of transition’, and the second dimension is related to the ‘influence of the incumbent regime’. Using these two dimensions, de Haan comes up with the eleven different transition paths that are summarized in Table 1.1.

### iii. Why do transitions manifest themselves in some specific ways?

Following the description of what happened, the next step is to explain why it happened that way, or how it happened (i.e. via which processes). Somehow related to taking such a step, Geels points out the need for ‘filling the MLP’ with more detailed accounts of actor

<table>
<thead>
<tr>
<th>Dominant pattern</th>
<th>With regime adaptation</th>
<th>Without regime adaptation</th>
<th>Failed transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstellation dominated</td>
<td>Radical reform</td>
<td>Revolution</td>
<td>Collapse</td>
</tr>
<tr>
<td>Empowerment dominated</td>
<td>Reconfiguration</td>
<td>Substitution</td>
<td>Backlash</td>
</tr>
<tr>
<td>Squeezed between reconstitution and empowerment</td>
<td>Teleological</td>
<td>Emergent</td>
<td>Lock-in</td>
</tr>
<tr>
<td>Adaptation dominated</td>
<td>Transformation</td>
<td>System breakdown</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1. Typology of transition paths by de Haan (2010)
activities that can explain what is happening at the regime and niche levels (Geels 2005b). As a preliminary effort, Geels proposes a set of mechanisms *(ibid.*) that are identified in some historical case studies. These mechanisms are summarized in Table 1.2. Geels discusses these mechanisms based on the transition phases they are encountered in^8^.

Table 1.2. Mechanisms of Geels (2002b)

<table>
<thead>
<tr>
<th>‘Emergence of novelty’ phase</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Add-on and hybridization</td>
<td></td>
</tr>
<tr>
<td>Spatial and geographical proliferation of technology</td>
<td></td>
</tr>
<tr>
<td>Outsiders are important</td>
<td></td>
</tr>
<tr>
<td>Saturation of existing markets</td>
<td></td>
</tr>
<tr>
<td>Importance of policy support in niche creation</td>
<td></td>
</tr>
<tr>
<td>Role of wide cultural visions and promises</td>
<td></td>
</tr>
<tr>
<td>‘Specialization and take-off of innovation’ phase</td>
<td></td>
</tr>
<tr>
<td>Linking up with growth in particular market niches</td>
<td></td>
</tr>
<tr>
<td>Emergence of specialized social groups</td>
<td></td>
</tr>
<tr>
<td>Rapid up-scaling</td>
<td></td>
</tr>
<tr>
<td>Strategic games and innovation races</td>
<td></td>
</tr>
<tr>
<td>Social struggles over technology</td>
<td></td>
</tr>
<tr>
<td>Hypes, bandwagon effects and self-fulfilling prophecies</td>
<td></td>
</tr>
<tr>
<td>‘Diffusion and competition against regime’ phase</td>
<td></td>
</tr>
<tr>
<td>Emergence of a dominant design</td>
<td></td>
</tr>
<tr>
<td>Sailing-ship effect</td>
<td></td>
</tr>
<tr>
<td>Resistance to change among regime actors</td>
<td></td>
</tr>
<tr>
<td>Missing the wave</td>
<td></td>
</tr>
</tbody>
</table>

Another relevant contribution is the MATISSE conceptual framework (MCF), which is proposed for developing simulation models for socio-technical transitions (Haxeltine et al. 2008). The framework is primarily used for developing simulation models that can replicate the transition *pathways* introduced by Geels and Schot (2007), which are discussed in the previous subsection. The framework includes a set of processes whose conjoint dynamics can replicate the different pathways. In that respect, MCF can be considered as a perspective to develop explanations for the dynamics in these pathways^9^.

The fundamental assumption behind MCF is related to the autonomy of the *regime* and the *niches*: it is assumed that they possess properties different from the ones of their constituents, and their dynamics can be explained in terms of processes at their abstraction level without referring to the processes at the level of individual actors or technologies. Based on this assumption, the processes proposed in the framework are all at the abstraction level of the *regime* and the *niche* entities. These processes include the ones related to the internal dynamics of these entities, as well as the ones related to their interactions (e.g. *niche* absorption (by *regime*), *niche* clustering, transformation (from *niche* to *regime*)). The extent to which the models that are developed according to this framework can achieve replication of the *pathways*

^8^ Referring to the four phases introduced earlier by Geels

^9^ Naturally, the processes of MCF can also be used to construct descriptive narratives of transitions. However, considering its primary objective, the framework is considered as an explanatory effort.
has been tested in a set of modelling exercises (Bergman et al. 2008; Köhler and Schilperoord 2008; Schilperoord et al. 2008).

The third notable explanatory effort is the pillar theory of de Haan, which is partially discussed among the descriptive efforts. The elements of the pillar theory (i.e. conditions, patterns, and paths) are proposed to have explanatory power besides their descriptive one. Such an explanation is, briefly, in the form of conditions leading to patterns, which lead to different conditions; and the chain goes on like that. These patterns are assumed to be emergent, regime-level processes; and they have explanatory power independent of the lower level processes that yield these emergent ones. In that respect, de Haan claims that there is no need to refer to lower level processes to explain the transitions, and his conditions and patterns are capable of providing such an explanation. In principle, the sufficiency of these conditions and patterns to construct an explanation is acceptable. However, no such explanation has been constructed and proposed so far. For example, some crucial issues for an explanation require answering questions on which pattern is triggered by which condition, or why a certain pattern takes place, but not another one. Such questions are yet to be answered. In summary, the pillar theory may be considered as providing modular pieces for an explanation, rather than providing an explanation. Therefore, it can be considered as standing somewhere in between descriptive and explanatory efforts.

1.4. Looking ahead: promising directions for analytical transition studies

Transitions stand as a complex dynamic phenomenon for scientific research, and as a modern challenge for policy-making. The analytical transition studies are of primary importance with respect to both of these challenges. First of all, the explicit common objective in the field is to understand and explain how transition dynamics unfold over time; hence, directly related to the scientific enquiry of the topic. Secondly, the novel policy interventions to be developed depend on the extent of the knowledge about the nature of transition dynamics; i.e. the outcome of the analytical transition studies.

The previous section provided an outline of the notable efforts that have been published so far in the field of analytical transition studies. The extent of the previous achievements is important, and it is already possible to trace the influence of the concepts and insights developed so far on the novel policy intervention approaches (e.g. strategic niche management, transition management). However, it would be far from reality to characterize the field as mature, and the scientific enquiry on understanding transition dynamics as completed. On the contrary, the former studies lay down strong foundations, but there is still much to be done to build up a comprehensive understanding about the dynamics of transition processes. Some directions along which improvement of the field seem to be promising and beneficial are discussed below, without claiming any priority over other possible directions.

a. Issues related to the conceptual frontier

As seen in the previously discussed review, all descriptive and explanatory efforts are based on MLP and its basic concepts; namely the regime and the niche. All those efforts reside at the abstraction level of these concepts, and the niche/regime concepts hold the leading role in the transition storylines. Some of the directions along which analytical transition studies may progress are related to this dominant abstraction level.
i. **Structuralist stance**

A structuralist stance can be summarized as relying on a (social) structure that is autonomous from the individual elements (e.g. individual person), which constitute the structure, in explaining a (social) phenomenon (Barker 2005; Pettit 1996). Neither MLP, nor the utilization of the niche/regime as conceptual boundaries necessarily possesses a structuralist stance. There is still some room for agency while reasoning about the dynamics at the micro/meso level, or within a niche, for example. This issue is already discussed among some scholars in the field (Berkhout, Smith et al. 2004; Geels and Schot 2007). However, when the niche/regime concepts are treated as emergent entities, the structuralist stance dominates the explanation. In cases where a regime is treated as an emergent entity, it possesses objectives, resources and intentions, and capability to act according to these, for instance. The changes in the system are described in terms of the actions of, and the relationships between these emergent entities. When this is the case, there is no reference to the actions of the elements that constitute these niches or regimes (e.g. individual actors) in the accounts of transition dynamics. Figure 1.4 provides a simplified depiction of the difference between the two interpretations mentioned here; regime/niche as a conceptual boundary vs. regime/niche as an emergent entity.

![Different perspectives on the regime/niche concepts](image)

In this context, the two explanatory frameworks introduced in the previous section (i.e. MCF, and the pillar theory) both rely on the emergent entity interpretation of the regime/niche concepts. Therefore, both can be claimed to take a strong structuralist position in analyzing societal transitions. MCF addresses the issue to a certain extent by extending the core of the framework with the support canvas (Bergman, Haxeltine et al. 2008; Schilperoord, Rotmans et al. 2008): the support canvas includes individual actors (e.g. users), and the actions of these individuals determine the dynamics of the support canvas. These dynamics in turn influence the internal dynamics of the niches and the regime, as well as their interactions. In this form, the agency is introduced into the framework to an extent. However, the dominance of structuralist stance is still apparent among the analytical transition studies. In that respect, progress is possible in two directions in order to strengthen the foundations of the analytical transition studies; either an explicit and strong justification of the structuralist approach should be provided, or the current explanatory efforts should be extended to incorporate more room for dynamics at the lower abstraction levels (e.g. level of the actors).
ii. *Collectives of non-equivalents*

This issue is also related to the use of regime-like\(^{10}\) emergent entities as the basis of analyses. As discussed above, the regime-like concepts are used as autonomous entities (or as *collective actors* as some scholars refer to them (Schilperoord, Rotmans et al. 2008)). According to this usage, these entities are depicted as constellations of actors, artefacts, physical infrastructure, and formal and informal institutions. This brings about a serious challenge, as will be explained.

For example, representing a group of homogenous actors as a collective agent is a straightforward aggregation issue (i.e. aggregation of equal entities). Under certain assumptions, the aggregation of heterogeneous actors into a collective agent (i.e. aggregation of non-equal, but equivalent entities) can also be justified, and the behaviour of the collective agent can be deduced. However, the collective agents, such as a *regime*, are composed of non-equivalent entities. This means that a regime-like entity contains actors of different types (e.g. societal groups, NGOs, firms, users) with different preferences, and resource stocks (Geels et al. 2004; Rotmans 2005). Furthermore, the systems subject to transition studies are not purely social ones. The social aspects in these systems change in mutual interaction with the technophysical aspects, or, with the widely used expression, the social and the techno-physical aspects co-evolve (Bijker 1990; Bijker 1995; Geels 2005a; Geels 2005c; Rotmans, Kemp et al. 2001; Schot and de la Bruheze 2003). In order to represent the behaviour of such a collective of non-equivalents over time with the behaviour of the higher-level abstract entities, one needs to postulate higher-level behaviour rules. These higher-level rules depict the way the abstract entities behave under certain conditions, and they actually represent the conjoint change effect of the lower-level dynamics under these conditions (see the micro-macro level correspondence problem simply depicted in Figure 1.5).

![Figure 1.5. Correspondence between micro- and macro-level changes](image)

The difficulty of postulating regime/niche level behaviour rules should be intuitively apparent to the reader considering the dynamic complexity of the actor-technology interactions just mentioned above. These rules would be easy to deduce if these micro level constituents were homogenous, non-adaptive, and not going through a sort of quasi-evolution. However, this is not the case in the transition context. Therefore, postulation of such rules, if a theory on transition dynamics will be built upon the emergent entities, stands as a serious challenge.

\(^{10}\) Referring to regime and niches

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Introduction

17
Furthermore, the acceptance of such rules will be dependent on the theoretical and/or empirical validation of them, which stands as another important challenge.

Although de Haan provides the ingredients of such rules for the regime and the niches (i.e. conditions and patterns), so far he avoids postulating the behaviour rules in this structure. That is the primary reason why we consider the pillar theory as being stronger in description rather than explanation. Haxeltine et al. formulate such regime-level behaviour rules in MCF, but no validation discussion that provides some empirical and/or theoretical grounding for these behaviour rules has been provided so far.

\textit{iii. Policy-relevance of the abstraction level}

From a theoretical point of view, the predominant abstraction level among the analytical transition studies provides simplicity and elegance to the explanations of transition dynamics. In that sense, the abstraction level can be considered as an appropriate choice. However, this abstraction level may cause difficulties when the empirical application of these concepts, and utilization of general findings for policy development and assessment purposes is an issue.

At a high level, these concepts and the developed insights can be very effective for general policy discussions, and can even be used to shape meta-policies. However, once the level of policy problem discussion starts getting fine-grained, then the applicability of the concepts becomes questionable. This is, simply put, related to bilateral translation between two different abstraction levels. The concepts from the higher abstraction level of the regime-like concepts, and the concepts at the abstraction level of the policy makers should have some correspondence with each other to establish a link, which is crucial for the applicability of any know-how based on the regime-like concepts. This involves the following:

- Translation of the regime/niche states and dynamics into the concepts observable/measurable by policy makers in a particular context (so that they can be used as decision inputs)
- Translation of the expected probable consequences of feasible policy actions into the abstraction level of regime-like concepts (so that alternative courses of action can be assessed).

In the case where the regime-like concepts are used as conceptual boundaries, this problem can be overcome by ‘filling in’ those boundaries with entities (actors, artefacts) and processes that are at a policy-relevant level. In the other case of treating the regime-like concepts as autonomous entities, establishing the aforementioned translation stands like a serious challenge to establish a link between theoretical developments in the transition dynamics field, and the policy-making domains. Both ways, there is room for development in the field.

\textbf{b. Issues related to the methodological frontier}

Whatever the scope or objective, all analytical transition studies emphasize a notion about the transition processes; their dynamic complexity. This complexity manifests itself in the form of non-linear development trajectories, path dependencies, counterintuitive consequences of simple policy interventions, systemic inertia, and other dynamic phenomena. Although conceptual foundations for understanding such phenomena have been developed in the field, there is still lot to be done for understanding, explaining and developing a solid comprehension about them.
The previous sections introduced several concepts that can serve as building blocks for developing such a comprehension. However, what is harvested so far in terms of understanding transition dynamics using these concepts is limited. As Geels mentions (2005b), transition dynamics are not driven by a single cause or process, but it is a set of simultaneous processes at multiple dimensions and levels that drive these change dynamics. A similar remark is made by de Haan (2010) when he mentions that “…in reality the processes described by the patterns are intertwined and simultaneously at play…” However, no thorough analysis has focused so far on this realm of dynamic complexity caused by intertwined and simultaneous processes, which lies at the heart of the problem of transition dynamics.

Considering the issue raised in the previous paragraph, transition scholars can be depicted as standing at the edge of a challenging terrain; dynamic complexity of transitional processes. The challenges related to this difficult terrain have been recognized and discussed already in the field. Furthermore, new concepts have been developed and proposed to describe this terrain. However, very limited effort has been spent on entering and exploring this terrain to improve the knowledge about its nature. From one point of view, this is normal, and the steps to be taken forward into this terrain may be just a matter of time. Such efforts need firm conceptual foundations, and the efforts had been focusing on that part so far. More efforts exploring dynamic complexity can be expected once these conceptual grounds are established. From another point of view, the lack of complexity exploration can also be related to the boundaries imposed on the scholars by their methodological choices. In that respect progress of the field of transition dynamics is also partially dependent on innovative methodological steps to be taken.

The dynamic complexity highlighted above clearly resides beyond natural human comprehension skills. Deducting the conjoint consequences of a small set of non-linear processes is not a straightforward task. In that respect, qualitative and deductive analyses and discussions do not offer much progress into the terrain of dynamic complexity. Until now, such approaches dominated the efforts in the field, and this can also be an important reason why progress into exploring dynamic complexity of transition is limited.

Therefore, a direction to progress along the methodological frontiers may be related to utilization of computational approaches. There has already been some tendency towards this direction in the transition dynamics field (e.g. Bergman, Haxeltine et al. 2008; Haxeltine, Whitmarsh et al. 2008; Timmermans et al. 2008). The strong social aspect and the role of contingency in the transition problem, however, raise serious concerns about the appropriateness of these methods. On the other hand, the dynamic complexity aspect clearly signals this type of method, which is predominantly used in the analysis of dynamic system behaviour in various domains. The complexity field is a source of inspiration for the transition field with the notions and insights developed. The correspondence between these two fields has been discussed on various occasions (e.g. Geels 2006a; Rotmans and Loorbach 2009). Going beyond the conceptual correspondences and metaphorical usage of the complexity concepts, it is also promising to consider adopting the predominantly quantitative computational methods used in complexity studies.

In short, significant methodological progress seems to be crucial for achieving the level of understanding that constitutes the ultimate goal of the analytical transition studies. This
progress is dependent on developing novel perspectives to apply computational approaches within the social and highly contingent realm of societal transitions.

1.5. The scope and objectives of this study

The term 'societal transition' refers to a wide range of transition processes, which can be classified into different subsets. On the one hand, these different types of transitions share important aspects that characterize them as transitions. On the other hand, they have very important differences, such as the relative importance of techno-physical or institutional aspects. This study focuses on a subset of transitional change processes rather than the societal transitions in general. The subset that is the subject of this study consists of the transition processes in socio-technical systems, which probably constitutes the most frequently discussed subset in policy and academic domains.

As mentioned earlier, analyzing the dynamic complexity of transition processes demands novel approaches that go beyond purely qualitative ones. Computational approaches have been considered as promising options for analyzing such dynamic complexity. Case-specific applications of this kind of approach exist, but there has been no comprehensive assessment of such approaches in general in the particular context of transitions. One of the main objectives of this study focuses specifically on simulation-supported analysis as a widely used example of such computational approaches. We aim to answer the broad methodological question of how and to what extent simulation-supported analysis can be used for studying transition dynamics (RQ 1).

In the course of answering this broad research question on the simulation-supported analysis approach, we investigate a set of sub-topics that are directly related to this methodological enquiry. Firstly, we focus on the overall fit between the problem (i.e. analyzing transition dynamics) and the approach (i.e. simulation): does the simulation approach fit with the nature of the enquiries related to transition dynamics? (RQ 1.1) In order to answer this sub-question, we review and discuss the nature of research questions in the context of transition dynamics, and the aspects of societal systems that provide the biggest challenges in answering these questions about transitions. The answer to the question is based on our assessment about the potential of the approach in answering these transition-related research questions about the societal systems.

Addressing research question 1.1 provides an overall assessment about the potential and the limitations of the simulation-supported analysis approach. However, considering the variety of different ways a simulation-supported analysis can be conducted, a further detailed investigation is required. We study different uses of simulation models from the literature, especially in the context of societal problems, in order to answer the following question; what are the expedient uses of quantitative models, and simulation-supported analyses for the transition dynamics field? (RQ 1.2)

Specifying the different types of uses allows us to make a more precise evaluation of the main challenges and shortcomings of the approach in addressing questions on transition dynamics. Considering the set of uses identified as an answer to the research question 1.2, we evaluate the major limitations of these different model uses. This evaluation can be summarized with
the following question; what are the major limitations of simulation-supported analyses in the context of transition dynamics? (RQ 1.3) Going beyond pointing out a set of limitations, we also aim to discuss their implications, as well as possible ways of minimizing them.

The three sub-topics mentioned above mainly focus on the utilization of simulation models once they are developed. The missing piece related to our broader methodological question (i.e. RQ 1) is related to the development of such models. Both the wide scope of the subject systems, and the type of change being analyzed (i.e. change in the system structure) distinguish the transition-related problems from more conventional problems analyzed through simulation-supported analyses. Therefore, appropriateness of the existing modelling paradigms is an important issue that needs to be addressed in assessing the potential of the approach for studying transition dynamics. This issue is the last sub-topic we focus on in our methodological enquiry; what are (the) appropriate modelling paradigms for different model-use schemes in transition dynamics studies? (RQ 1.4) As a preliminary step towards answering such a question, we identify the requirements of the task at hand; which aspects of the subject system need to be explicitly represented in the model, and in what ways they should be represented. The answers to this type of questions lie in the way a transitional change and its important drivers are conceptualized. Therefore, we first review conceptual representations used in the literature on transitions. Based on the outcome of this review, we investigate a set of modelling paradigms in order to assess whether they are compatible with the ways transitional change is conceptualized. In other words, whether the modelling paradigm can be used to represent the key processes and elements of transitional change dynamics. This way we aim to point out appropriate approaches, as well as their strengths and weaknesses in serving different objectives within the transition dynamics field. In this assessment, we benefit from purely methodological literature on these modelling paradigms, and also from a set of published applications of each of the considered modelling paradigms. This way we synthesize the existing methodological discussions, and our assessment of the paradigms from the perspective of a transition scholar.

However promising the simulation-supported analysis would be, the potential of the approach could only be realized if proper conceptual foundations exist to study transition dynamics in general. While case-specific applications of the approach are relatively more straightforward, these applications contribute very little to the general understanding about transition dynamics. Using simulation-supported analysis to study transition dynamics in a context-free manner demands a general conceptual representation (i.e. a model) for the subject systems; a representation that incorporates transition-relevant aspects and processes in these systems. The existing conceptual models in the literature are either under-developed, or too abstract to constitute such foundations for the approach. The second main objective of the study is related to developing such conceptual foundations for simulation-supported analysis in the field, while addressing the identified problematic issues with the existing conceptualizations. This objective can be summarized via the following question; is it possible to develop a conceptual framework that applies to a range of socio-technical systems, and is appropriate to be used for simulation-supported analysis of socio-technical transitions? (RQ 2)

This second research question is related to a design/development process during which a general framework that serves developing purely conceptual and/or quantitative models for systems in transition is developed. A fundamental piece of such a framework is the set of key
concepts that will be used to depict the state of a system at a certain time point. The first step of developing a general conceptual framework is related to this point, and can be summarized with the following sub-question; what are the basic conceptual blocks to depict the state of a socio-technical system in transition? (RQ 2.1)

Since the problem of concern is mainly related to the dynamics of the systems during a transition, a static conceptual depiction of the systems alone is not satisfactory for analyzing transition dynamics. A proper general conceptual framework should also cover the interactions between these building blocks, as well as processes that alter their states over time. This issue constitutes another important piece of the conceptual framework design process;

- How are these building blocks interrelated in the context of transitional change? (RQ 2.2.)
- What are commonly observed ways in which these building blocks go through transitional change processes? (RQ 2.3)

In the course of answering these questions (i.e. RQ 2.1-2.3) we mainly adopt an induction-based approach. As a preliminary step, we have reviewed the general literature on large-scale socio-technical systems, and innovation diffusion. The general frame of the conceptual framework has been shaped by this review. This is followed by investigating a series of detailed case studies from the literature. Some of these case studies have a large-scale socio-technical system as the subject. Some others have narrower scopes, and they discuss developments related to some sub-systems, or basic components of the socio-technical systems, such as infrastructures, or individual technologies. In this investigation, we focus on distilling the factors and processes that play important roles in the way the key components of socio-technical systems, or the whole system changes over time. In other words, we aim to extract change processes that can potentially play an important role in shaping the development trajectory during a transition process. The approach used in this distillation process is mainly inspired by the grounded theory approach (Glaser and Strauss 1967).

As an outcome of the development process, we aim to have a general conceptual framework for simulation-supported transition analyses, which builds on the premises such as the importance of taking agency into account, policy-relevance of the used abstraction level, and distinct representation of non-equivalent elements of the socio-technical systems. However, both the importance of these premises, and the extent to which the proposed framework can serve as a general one for simulation-supported analyses are claims that are supported more with reasoning, rather than factual evidence. In the third part of our study, we take the developed framework for a ‘test drive’ in order to collect concrete evidence to support these claims. In order to do so, we study three transition cases from different socio-technical contexts using the models that are developed using the developed conceptual framework.

The primary objective in conducting these three modelling exercises is two-fold; we aim to identify and illustrate a set of circumstances under which the three basic premises are relevant and important on the one hand, and to explore the feasibility of using the proposed framework as a general conceptual grounding for simulation-supported analyses of transition dynamics on the other. This latter aspect of the primary objective is related to a set of issues. First of all, we aim to investigate the extent to which the framework can be used in different socio-technical contexts, which relates to the generality claim. Secondly, we explore the
conceptual and practical limitations of the proposed framework. The conceptual limitations are related to the difficulties encountered in representing particular issues and/or processes from the actual transition context using the conceptual elements of the framework. In a sense, this is related to the limitations of the framework in its conceptual coverage. The practical limitations correspond to the plausible difficulties in representing the concepts of the framework in quantitative simulation models, which demands quantification of the concepts and formalization of the processes. The practical limitations relate to the extent to which the framework is compatible with simulation-supported analyses.

In brief, the primary objective in conducting the three modelling studies is to investigate and to demonstrate the usability of the framework as a conceptual grounding for studying transition dynamics. Besides this primary objective, we also aim to put forward some different examples of simulation-supported analysis of transitions. By providing concrete examples of the model uses identified in our answer to the research question 1.2 (i.e. what are the expedient uses of quantitative models, and simulation-supported analyses for the transition dynamics field?), we aim to link the first part of the study, which is more focused on the approach, to the second part, which is conceptual. Furthermore, these modelling studies are also expected to provide a sharper picture on the type of insights that can be developed related to transition dynamics and socio-technical systems by using such models. Finally, and most importantly, based on the general conclusions and the evidence from these three modelling practices, we reflect on the relevance and the added value of having a general explanatory framework in transition studies, which is a fundamental premise of the study.

As mentioned earlier, the ultimate aim of this research is to come up with an analytical perspective to study transition dynamics. Such a perspective naturally comprises of both methodological and conceptual components. The list of questions provided above guide the development process of such a perspective along both of these frontiers, which constitutes the main subject of the following chapters of this dissertation.

1.6. Organization of the dissertation

The dissertation comprises three main parts. Part I, which includes Chapters 2 and 3, is devoted to the simulation-supported analysis approach, and considers the approach in the particular context of transitional change processes. Chapter 2 investigates the potential uses of the approach, as well as its shortcomings, in analyzing dynamics of transitional change processes. Following this, Chapter 3 reviews existing modelling paradigms that may constitute a basis for, or at least contribute to, modelling studies in the transition dynamics field.

Part II introduces the actor-option framework, which is proposed as a general framework for developing conceptual models for socio-technical systems taking into account their internal processes related to transitional dynamics. Chapter 4 introduces the basic concepts of the framework, and discusses the general scheme of interaction according to which these concepts are interlinked. Chapter 5 complements this general scheme of interaction by specifying a set of change mechanisms that drive internal change processes in the socio-technical systems along a transition process. The final chapter of Part II, i.e. Chapter 6, provides an overview, and aims to position the actor-option framework within the existing studies in the transition dynamics field. In order to do so, the actor-option framework is compared and contrasted with other conceptual frameworks/perspectives in the field.
Part III is primarily about the assessment of the *actor-option framework*, especially when it is used for simulation-supported analyses of transitional change processes. The first chapter of the part, i.e. Chapter 7, introduces general guidelines for using the framework and developing (simulation) models for a socio-technical system under scrutiny. The following three chapters, i.e. Chapters 8, 9, and 10, report three simulation-supported analyses in different socio-technical domains. These modelling studies aim to demonstrate and to explore the applicability of the framework as a general one, and also the type of insights that can be developed via simulation-based exploration of the models developed based on the *actor-option framework*. The part concludes with Chapter 11, which reflects on the *actor-option framework* based on the observations from three modelling studies.

The dissertation concludes with Chapter 12, which summarizes the major contributions of this study. Furthermore, the chapter also includes a reflection on the overall research process and the outcome, which reveals some potential shortcomings and prospective directions of research.
As already discussed in Chapter 1, one of the major objectives in the transition studies field is to understand the complexity of transition dynamics. Conceptual foundations for studying such dynamic complexity have already been developed, but the progress in our understanding about these dynamics has been limited. We claim that one of the important factors that hamper such a progress is related to the set of approaches used for inquiries on transition dynamics. The predominantly used qualitative approaches do not fit the challenge of exploring the terrain of dynamic complexity that lies beyond the point at which the transition studies field is standing at this stage.

Computational approaches in general, and computer simulation in particular, are considered as promising alternatives for studying dynamics of complex (adaptive) systems by many scholars, including the author. There has already been a set of examples that rely on this kind of approach in the transition field (e.g. Bergman, Haxeltine et al. 2008; Faber and Frenken 2009; Timmermans, de Haan et al. 2008). Although methodological discussions appear in these studies, these discussions are generally confined to the particular case-specific context of the study. A comprehensive and in depth discussion on the use of the simulation-supported analysis approach in the context of transition dynamics is still largely absent.

In Part I of the dissertation, we aim to address this methodological void, and present the outcome of our general methodological investigation of simulation-supported analysis for studying transition dynamics. As the first step of this investigation, we make a comprehensive problem-approach fit assessment, which is presented in Chapter 2. This assessment clarifies a set of different uses of simulation-supported analysis to address different needs within the broader transition dynamics problem. Moreover, the chapter also lays down the major limitations of the approach considering the nature of the particular type of systems studied, and the type of questions raised related to transition dynamics. In short, Chapter 2 focuses
on ‘using simulation models.’ In Chapter 3, we focus on another important issue; ‘developing simulation models.’ The chapter reviews a set of modelling paradigms, and discusses their appropriateness for transition studies. Strengths, as well as weaknesses of different approaches are considered while trying to answer the question of whether a particular paradigm can address the needs of simulation-supported studies on transition dynamics better than others. The part concludes with a general discussion based on the main outcomes of our investigation reported in Chapters 2 and 3.
Simulation-supported Analysis

2.1. Simulation and simulation models

The term ‘model’ refers to various concepts in differing domains. A model, in general, can be defined as a simplified description of an object/system that shares important properties and characteristics with the original object/system. According to Rothenberg (1989), a model is ‘a representation of some referent object that can yield the answer to a question about this referent object more efficiently than the referent object itself.’ As can be deduced from the Rothenberg’s characterization, the question to which an answer is sought with a model (i.e. the modelling question) dictates the set of important properties and characteristics of the real object/system that should be represented by the model. A model can be very different in nature, such as mathematical (i.e. a model where the description is in terms of mathematical statements), computer-based (i.e. a model where the description is in terms of computer instructions), or conceptual (i.e. a model where the description is in terms of verbal or written statements), to give some examples. In this chapter, the focus is on a specific subset of this variety of models, which is the subset of computer-based simulation models. The word simulation comes from the Latin verb ‘similare’, which means to imitate or mimic (Sterman 1991). A simulation model can be described very briefly as a simplified representation of a real system, in which the principal aim is to imitate the behaviour of the real system over time. Throughout the chapter, this type of model will be discussed in the context of studying transition dynamics. Hence, in the remainder of the chapter the term ‘model’ refers to this specific subset of models, unless otherwise stated.

Roughly speaking, a model includes two important aspects of a system in order to imitate its behaviour over time. The first of these is a state description. This includes the key indicators, variables, and/or concepts that are sufficient to describe the state of the system at a particular point in time. This set of variables depends to a large degree on the purpose of the modelling study. For a modelling study focusing on the amount of water a community can use, the biodiversity level in the water may not be relevant. However, the very same indicator may be a crucial part of the state description for another study focusing on the fauna of the same water
system. Hence, the aspects of the system that have to be represented in the state description are solely dependent on the phenomena being studied and the objective of the modelling study.

However, just representing the state of the system is not enough. This only provides a static depiction of the system. Since the purpose of the model is to mimic the behaviour over time, a second component is essential. This is about how the system changes over time: given the current state of a system, in which way the system will be changing. This includes relationships among system elements, the rules/routines according to which these elements change, and the time-dependent functions that alter the elements. This second component of the model can be seen as the driving motor of the simulation, since it specifies how the system will evolve over time given its initial state. In other words it is the set of drivers of change in the model.

To summarize, a model can be depicted as a transformation machine, which transforms the state description of the system according to the specified drivers of change. Simply put, it takes the current state, and then processes this information according to the transformation function, i.e. drivers of change. The outcome will be the new state of the system. Doing this in a recursive manner, a model generates a time-path of system indicators/variables.

Simulation models have been used widely in, for example, engineering, policy analysis, and ecological systems to investigate dynamic problems (e.g. Bunn and Larsen 1997; Fiddaman 2002; Moxnes 1998; Wiegert 1975; Yücel and Barlas 2010). Appropriateness of simulation-supported analyses for studying such dynamic problems suggests that the approach can also be an effective one in the transition dynamics field. Although this claim is intuitively acceptable, the fit between the problem and the approach should be considered thoroughly. In the following section, we focus on this issue by considering the characteristic aspects of the research questions related to transition dynamics, as well as the nature of systems to be modelled in order to answer these questions.

2.2. Analyzing transitions through simulation: does the approach fit the problem?

The increasing interest in transitions as a new research topic is mainly due to the fact that it appears to be one of the most challenging problems for policy makers. A transition, with a very simple depiction, can be pictured as a process of change, during which a system experiences a significant structural change. Different strands of transition studies focus on different issues related to these change processes: process-oriented transition studies are interested in developing approaches for steering transitions (Kemp et al. 2001; Loorbach 2007; Voß, Bauknecht et al. 2006), whereas, analytical transition studies focus on developing insights about this change process, for example, via identifying underlying mechanisms and factors (de Haan 2010; Geels 2005b; Rotmans 2005). Despite differences in focus and approach, these strands have a very important common point, which also characterizes the transition studies, in general: it is the path taken and the way this path is shaped that is of interest, rather than the final state of the system. The quote from Le Guin summarizes the common perspective in transition studies very well:

“It is good to have an end to journey towards; but it is the journey that matters, in the end” (Le Guin 1969, p. 220).
In historical accounts of transitions, the path-dependent nature of the end-state is very clear, since the depictions focus on the co-evolution of the system and its environment during the transition process. The transition management perspective builds upon the clear assertion that a final state of a transition process cannot be forecasted or predetermined. This end-state depends on the path taken; hence it is the path that should be steered to achieve a desirable, yet unknown state. The importance of the system's behaviour over time is even more evident for studies on transition dynamics. In short, transition studies can be characterized as a type of study of dynamics, rather than a study of equilibrium states. For example, neo-classical economics is mainly interested in equilibrium states, but not that much on the path taken between different equilibrium points; hence it qualifies for the latter type. Such an approach serves little, if any, for transition studies and, furthermore, it is against the fundamental foundations of transition studies. The emphasis on understanding the dynamic path taken as the system shifts from the old to a new structure is crucial, since it determines the methodological requirements and challenges.

The focus is on the dynamics of a socio-technical system. However, the main characteristics of such systems make it difficult to analyze and understand these dynamics. These are large-scale societal systems that comprise multiple sub-systems, such as social, economic, technological, and/or ecological ones. These sub-systems all have their internal dynamics, and they condition the dynamics of the other sub-systems as they interact. In some cases, it is a challenge even to analyze the dynamics of a single sub-system in isolation, such as the social one. The social aspect of socio-technical systems comprises a multiplicity of actors acting based on their preferences, norms and powers, which may show enormous variety (i.e. multi-actor aspect of the transitions (Rotmans 2005)). Even with a considerable level of understanding of how each of these actors acts individually, in most cases it is hard to foresee the long-run system-level consequences of the simultaneous actions of these multiple actors.

Additionally, socio-technical systems are densely woven with feedback interactions. A decision made by an actor (e.g. investment) alters the system conditions (e.g. demand-supply balance), and this influences the future actions of the same actor. As a social sub-system interacts with the ecological and/or technological sub-systems, high-level feedback relations can also be recognized between these sub-systems. Feedbacks with differing time scales are observed between social, economical and ecological systems, for example, in the context of global warming. Anthropogenic carbon emissions during the last couple of centuries altered the ecological balances leading to global climate change via changing atmospheric carbon levels. This effect has direct effects on the social system via influencing food production, and water related problems. Additionally, the recognition of the problem also alters the norms and values, which leads to initiatives for changing the daily practices, economic activities and technologies used in artefacts. The changes in the social, economic and technological systems in turn influence the ecological system completing this high-level feedback. In short, socio-technical systems are very rich in feedbacks that operate at different levels of the system, and with different time scales. While the interplay of even a small set of feedbacks is sufficient to carry a system behaviour beyond easily comprehensible levels (see Sterman (1989), for example), this richness constitutes a serious challenge for transition studies.

Furthermore, the multi-actor and the feedback-rich natures of socio-technical systems also possess other features; firstly, the interactions are not necessarily instantaneous in these
systems. The effect of an action may be realized after a significant time delay at the source of the action. The recognition of the environmental damage caused by carbon emissions took more than a century to recognize, for example. These delays in the feedback loops that decouple the cause and effect in time make it even more difficult to understand the dynamics of such systems. Finally, most of the interactions in these systems are far away from being linear in nature, which indicates that a change in one aspect of the system may not always yield a change in a comparable magnitude in other aspects of the system.

These features of large-scale socio-technical systems that are discussed above yield dynamic complexity (Sterman 1994) observed in these systems. The complexity caused by the very nature of these systems, which is also discussed elsewhere (Geels 2006a; Rotmans 2005; Rotmans and Loorbach 2009), takes the issue of understanding unfolding transition paths beyond the intuition level of scholars in the field, and the limits of purely qualitative approaches. One of the fundamental characteristics of the dominant perspective in transition studies stems from the recognition of this dynamic complexity. In transition studies, it is assumed that transitions are path-dependent processes that may radically change their courses due to contingencies. Therefore, prescriptive and predictive efforts do not have any relevance in the context of transition dynamics according to this perspective. In that respect, analytical efforts focus on developing insights about the way socio-technical systems behave, and on understanding the system-level consequences of changes in the sub-systems or the constituents of the system.

Considering the main points highlighted above about the general foundations of the transition studies (i.e. the focus on understanding the dynamics and the basic assumptions on the unpredictability of the transition process), computational approaches, and specifically simulation-supported analysis, appear as appropriate tools. First of all, simulation, by definition, stands as an appropriate approach when the subject of inquiry is the behaviour of a system over time, as is the case in transition studies. Secondly, simulation is predominantly a descriptive approach, rather than a predictive (e.g. regression), or a prescriptive (e.g. optimization) one. This also fits well with the dominant perspective in transition studies mentioned in the previous paragraph.

When we consider the problematic nature of socio-technical systems when it comes to analyze their behaviour (i.e. dynamic complexity challenge), simulation-supported analysis appears as a promising approach. As introduced in the previous section, simulation models include a state description of the system being studied, as well as a set of interactions that describe how system elements influence each other and change over time. First of all, this aspect of models enforces the development of a structured and consistent conceptualization of the system. The most important benefit of simulation-supported enquiries on transition dynamics is the possibility of generating possible system behaviours. Even in cases where the processes and the factors conditioning the dynamics of the system are understood well in isolation, the difficulty arises when these processes and factors are considered simultaneously, and the dynamics to emerge are hard to foresee. That is exactly what models serve for: creating the evolution of the system behaviour over time. This makes models promising test-beds, i.e. artificial societal systems, for enquiries about the transition dynamics.

The transition studies field is a relatively young one. Despite this fact, there exist some examples, though limited in number, that demonstrate the methodological fit and potential contributions
of simulation modelling (e.g. Holtz 2008; Safarzynska 2009; Schilperoord, Rotmans et al. 2008; Struben 2006; Timmermans, de Haan et al. 2008; Weisbuch et al. 2008). These early simulation-supported transition studies provide considerable supporting evidence regarding the degree of problem-approach fit, which suggests that simulation modelling can have an important place in the methodological toolbox of transition studies. Furthermore, this place in the toolbox is also naturally inherited from the ‘progenitors’ of the transition field, which contributes to the theoretical and methodological foundations of the field. Among others, the impacts of certain progenitor fields are more visible: the more influential ones include diffusion studies, integrated assessment, evolutionary economics, and complexity theory.

Diffusion in general, and diffusion of innovations in particular, has been the subject of numerous empirical and theoretical studies in various domains, such as sociology, economics and marketing (e.g. Bass 1969; Granovetter 1978; Hedström and Swedberg 1998a; Mahajan and Peterson 1985; Meade and Islam 2006; Nakicenovic and Grubler 1991; Rogers 1983; Young 2007). Similar to transition studies, the emphasis in diffusion studies is on the diffusion behaviour over time, and factors that play an important role in the shaping of this behaviour are related to information flows (e.g. word of mouth, advertisement), social behaviour (e.g. imitation, network externalities), and technological developments (e.g. learning-by-doing, scale economies, spillovers). Early analytical models capture some of these aspects in a very elegant manner (Geroski 2000; Mahajan et al. 1991; Mahajan and Peterson 1985; Parker 1994), but the dynamic complexity caused by the combination of these aspects is beyond being analytically tractable. This made simulation models a very important, and probably the dominant approach, used in diffusion studies recently. This can be observed in various studies in the field (Abrahamson and Rosenkopf 1997; Cantono and Silverberg 2009; Dattee and Weil Birdseye 2007; Hazhir and Sterman 2007; Hohnisch et al. 2008; Homer 1987; Janssen and Jager 2002; Schwarz and Ernst 2009; Valente 1996; Zenobia et al. 2009).

The development of the Integrated Assessment (IA) approach is mainly triggered by global environmental problems of the 20th century. Ozone depletion, acid rains, and global climate change are the problems that attracted most attention in this field (e.g. Amann et al. 1999; Rotmans 1990). As is apparent from these examples, the problems studied with the IA approach are large-scale ones with social, ecological, economic and technological aspects, which cross the boundaries of any conventional field (Rotmans and van Asselt 1999). IA was developed as a result of the recognition that these issues demand integrated policies utilizing existing knowledge from various scientific disciplines. In that respect, the roots of the approach are in modelling communities seeking to develop tools to advance understanding of the human-climate system (Parson 1995). The methods in the toolbox of IA are not confined to simulation models, and include other analytical methods, as well as participatory approaches. Nevertheless, IA models, which are large-scale computer simulation models, are the predominant means for IA studies. These models are developed by integrating biophysical and socio-economic processes, and used to answer specific policy questions (Parson and Fisher-Venden 1997).

While simulation gained popularity over time in diffusion studies, it has been a primary approach from the beginning in the evolutionary economics field. Since the seminal work of Nelson and Winter (1982), which is an early milestone of the field, simulation models have been heavily utilized. As Dosi and Nelson state, the purpose in evolutionary economics is
“to explain the movement of something over time, or to explain why that something is what it is at a moment in time in terms of how it got there” (Dosi and Nelson 1994, pg. 154). This explanation relies on mechanisms that increase the variation among constituents of the system (e.g. firm-level strategies, or technologies used) on the one hand, and the ones that reduce variation via selection (e.g. market competition) on the other. The focus is on non-equilibrium processes, rather than equilibrium states, opposed to the case of neo-classical economics. The phenomena of interest include macro economic growth, technological development, innovativeness, or sectoral/firm-level change. The emphasis on the behaviour over time and underlying mechanisms coupled with the importance of heterogeneity (among firms, technologies, consumers, etc.) and bounded rationality make simulation the primary method in the field (Dosi et al. 2006; Faber and Frenken 2009; Janssen and Jager 2002; Radzicki and Sterman 1994; Safarzynska and van den Bergh 2009; Saviotti 2003; Tesfatsion 2001; van den Bergh 2004; van den Bergh et al. 2006; Verspagen 2009; Windrum and Birchenhall 2005). These models are mainly used for the reproduction of stylized facts (i.e. well-established empirical regularities), such as skewed firm size distribution, clustering of innovative activity in space and/or time, by relying on evolutionary mechanisms of variation and selection (Frenken 2006). Less frequent examples are used to replicate particular empirical cases, as in the case of ‘history-friendly’ models, as Malerba et al. (1999) label them.

The establishment of the Santa Fe Institute marks the birth of complexity as a field of study (Waldrop 1993), which had a significant impact on various fields such as physics, biology, ecology, economics and sociology. Broadly, complexity studies focus on the link between the macro and the micro: how can macro-level phenomena be explained in terms of its micro-level components’ (such as atoms, cells, organisms or individuals) interactions (Coveney and Highfield 1995)? However, reasoning about the macro-level consequences of the micro-level interactions, especially when the interacting elements are adaptive as in the case of social systems, is not straightforward. As Miller and Page states, ‘...even if we can fully uncover the micro-foundations of behavior, ...we may still not have a simple way to understand their macro-level implications’ (Miller and Page 2007, pg. 67). Mainly driven by this challenge, computation and simulation models established a strong position in this field, and have been used and proposed as the approach in numerous complexity-inspired studies (Anderson 1999; Axelrod 1997a; Axelrod 1997b; Epstein 2002; Frenken 2006; Holland 1998; Kohler and Guerman 1999; Nowak and Latane 1994; Rasmussen and Bonnett 1995; Shalizi 2006; Wolfram 1986; Wolfram 2002). In this field, the models have been used as dynamic exploratory tools in attempts to discover the adequacy of particular mechanisms to explain emergent phenomena (e.g. a pattern, structure or behaviour) at a higher (i.e. macro) level.

The aforementioned four fields can be considered as both theoretical and methodological progenitors of the transition studies field. From the theoretical perspective, they provide the foundations regarding the sub-problems like innovation, diffusion, co-evolution, and the micro-macro link. They also influence the conceptual frameworks used to analyze transitions. Apart from this (partial) overlap regarding the problem at hand, another important overlap is apparent in the nature of the overall objectives: it is an explanation, understanding or insight that is sought after, rather than a solution, prescription or prediction. This dual overlap indicates that it is not just the basic concepts that may be inherited from these fields, but also the utilized methodological approaches, among which simulation modelling is an important

1 Emphasis added later
one. In that respect, considering the similarity in the nature of the problems studied and
the dominant perspectives in approaching such problems, the wide utilization of simulation-
supported analyses in these four fields suggests that the approach has the potential to establish
an important place in the toolbox of the transition scholars.

This section provided a problem-approach fit assessment at a very general level. However,
both problems in the transition studies field, and the ways simulation-supported analyses
can be conducted demonstrate variety. For example, simulation-supported studies from the
aforementioned four progenitor fields, despite not focusing solely on transitions, provide
valuable insights about different ways these models can contribute, as well as potential
shortcomings of the approach. In the following section, we will be focusing on this variety
and discuss different model uses that are appropriate and potentially useful in the transition
dynamics context.

2.3. Different uses of modelling and simulation in the transition studies field

As a research method, simulation modelling entered the portfolio of the physical sciences
and engineering a long time ago (e.g. Wiegert 1975; Youle et al. 1959). The diffusion of the
method in the social sciences, on the other hand, took place later, and the method has been
going through an important evolution during this diffusion. Although the technical aspects
of the method are the same, significant changes are observed in the type of questions tackled
by the models, and in the ways the results are interpreted. As a consequence of this ongoing
methodological evolution, it is possible to identify different uses of the models in studying
social phenomena (Axelrod 1997a; Yücel and van Daalen 2009a). Some of these uses are
highly relevant for transition studies, and three such uses of simulation models that differ
primarily in the main objective they serve are discussed in this chapter.

The following sub-sections introduce three different uses of simulation models that are
considered to be relevant for transition studies in our investigation. In most cases it is possible
to associate a given model with one of these uses, but in some other cases a single model may
serve more than a single objective. That is indeed possible: hence, the three types of model
use do not constitute an exclusive categorization. However, in most of the cases one of these
objectives is dominant, and can be used to characterize the model.

a. Model-use for case-specific insight development

This is probably the most widely known utilization of models as a research tool. It focuses
on building a ‘realistic’ model of a system, with respect to certain aspects, and then utilizing
this model as a ‘synthetic reality’ or ‘reality in silico’ in order to conduct scenario and policy
experimentations. The main goal in these studies is to develop a better understanding about
the behaviour of a particular real-world system by using its simplified version, the model, as
an experimental ground (e.g. Rotmans 1990; Stadler et al. 2007; Stroud et al. 2007). Although
the results obtained from the models are not ‘predictions’ about the future, they reveal the
potential dynamic consequences of endogenous system dynamics with given policies, which
might be challenging to comprehend in the absence of such a simulation model.

The models serving this purpose are generally detailed in order to establish the link to the real
transition case being studied. Building a simulation model –a replicate of reality– to be used for
experimentation primarily demands a solid knowledge base about the system being modelled.
So, one of the characteristics of this type of model-use is the reliance on a solid knowledge base about the real system. Apart from that, the knowledge base is generally composed of widely accepted theories and empirical data, rather than speculations and hypotheses, regarding the system components and the relationships between these components. The added value of this type of model-use is related to the whole-parts distinction: understanding the individual parts of a system may not be enough to understand the whole. A good depiction of the system (e.g. information about the main parts/elements, and relationships among them) is necessary, but not sufficient to deduce the overall system behaviour. The internal dynamics of the system may be so complex (e.g. due to non-linearity, great number of interacting components, stochastic nature, etc.) that it is not possible to determine system behaviour analytically or to foresee it just by thinking on the system based on the well-established description of it. In these circumstances, the simulation model acts as an experimentation platform. The time evolution of the complex interactions embedded in the system can be traced by simulation. In this way, different settings, scenarios and policy options can be tested on the simulation model, which can be considered as a simplified prototype of the real system with respect to experimenter’s concerns (e.g. Ferguson et al. 2006; Stadler, Kranzl et al. 2007; Stroud, Del Valle et al. 2007). This type of model-use is common in policy studies, and the application is straightforward in cases where the problem domain is a stable socio-technical system. However, since a transition implies a change in the structure of the socio-technical system, the uncertainty regarding how to represent the system, how to validate this representation, and how to conduct experiments are serious challenges. This point will be elaborated in Section 2.4, where shortcomings of simulation-supported analysis in transition studies are discussed.

In the transition domain, the set of modelling works by Struben is a good example of such model-use (Struben 2006; Struben and Sterman 2008). These models focus on the transition to the alternative fuel vehicles from the incumbent internal combustion engine regime. In doing so, the models incorporate consumer awareness and choice theories, technology-side development mechanisms such as learning-by-doing, economies of scale, network externalities and infrastructure complementarities. In short, the model brings together a set of well-studied and accepted theories and assumptions from different domains, and provides an integrated whole which enables studying the dynamic interactions between these processes and their implications in terms of transition dynamics. Additionally, the models are calibrated to resemble the California district. Struben identifies some important challenges regarding this transition, and assesses a set of policies designed to foster a transition. In a similar manner, Chappin and Dijkema (2009) use a model as an experimental ground to study the potential impact of carbon abatement policies on the transition in the Dutch electricity system. As in Struben’s works, this model also incorporates directly observable or intuitive concepts and processes (e.g. profit-oriented generation companies, liberalized Dutch energy market, commonly accepted investment and forecasting heuristics, technological development via learning-by-doing). Whitmarsh and Nykvist (2008) conduct a scenario and policy analysis study regarding the land-based mobility transition in UK. The model, which is based on the concepts proposed and tested elsewhere (Bergman, Haxeltine et al. 2008; Haxeltine, Whitmarsh et al. 2008; Schilperoord, Rotmans et al. 2008), is used to assess the impact of different policies on mobility choices given different possible future scenarios.

As seen in the examples, this kind of model use is primarily interested in studying possible transition dynamics under differing scenario settings, and the impact of certain policies on
these dynamics. As a natural consequence of this type of overall objective, the models used here are case-specific and rich in detail regarding the system being focused on. In other words, these models are custom tailored and fine-tuned for a specific transition problem. Boero and Squazzoni (2005) label such models as ‘\textit{case-based models}’ in their taxonomy.

\section*{b. Model-use for generic insight development}

There are some generic processes that are observed to be influential in different transition cases. For example, economies-of-scale, and learning-by-doing are some examples of such processes in socio-technical transitions. Due to their significance in shaping the transition dynamics, developing a generic understanding about such processes is important. This type of model-use focuses exactly on this issue. The subject of the model is a specific mechanism (or a set of these), rather than a particular real-world system in this type of model-use.

The models used for this purpose are developed independent of a particular context (i.e. loose ties with empirical data), and the model is used to explore the dynamic consequences of the subject mechanisms’ interaction under different conditions. The seminal work of Arthur (1989) on \textit{returns-to-scale} is a very good example of such a use. The model, which depicts technology competition in the existence of increasing returns, is an generic one, i.e. it does not correspond to any particular real-life case. However, the exploration based on this model leads to very valuable insights regarding situations where increasing returns have strong influence, besides other mechanisms, in an innovation diffusion or technological competition context. In other words, these models are used to investigate the dynamic regularities that apply to a range of empirical cases that share some common features.

This model-use scheme has been used in several transition studies, most of which focus on the ‘\textit{diffusion of the novelty}’ aspect of the transition processes (e.g. Cantono and Silverberg 2009; Weisbuch, Buskens et al. 2008; Yücel and van Daalen 2009c). These models are used to explore mechanisms like information diffusion, willingness-to-pay, and social imitation (e.g. bandwagon effect). Despite being abstract models, the results obtained from these models via extensive experimentation provide valuable insights about the way the mechanisms interact. Another example is by Windrum and Birchenhall (2005): they investigate the impact of network externalities in terms of creating barriers for the new coming successor technology, and how and under which conditions these barriers may be overcome. Similarly, Yücel and van Daalen (2009b) conduct an exploration regarding strategic niche management (SNM) (Kemp, Rip et al. 2001; Kemp, Schot et al. 1998) using a generic model that depicts various implementation schemes and system conditions. The analyses demonstrate that depending on the characteristics of the existing \textit{regime}, as well as the development potential of the \textit{niche}, some SNM implementations may lead to very ‘expensive’ failures; a conclusion which would be hard to draw based solely on a qualitative analysis. Examples focusing on the role of evolutionary processes on determination of possible transition paths also exist. To mention a couple, Janssen and Jager (2002) focus on the co-evolution of two interrelated domains in a technological substitution problem; consumers and firms. The variation creating mechanisms and the selection environment in both sides constitutes the locus of their model-based exploration. Faber and Frenken (2009) provide more examples of models used for exploring evolutionary mechanisms in the context of technology substitution and transitions in their review article.
As is evident from the description above, the models used for this purposes do not correspond to any particular case; hence, they are referred to as *abstract* or *generic* models in the text. Boero and Squazzoni (2005) refer to this type of models as ‘typifications.’ Since the objective is to understand the subject processes in a generic form, a wide range of possible occurrences of the same process need to be analyzed. Therefore, the defining characteristic of this scheme is the extensive number of simulations in order to explore the feasible model instances (i.e. different instances that can be created by varying the model variables or structures). Designing this exhaustive exploration, as well as interpretation of the numerous results is the cost paid in return of the insight to be developed.

c. **Model-use for theory development**

An important research strand in transition studies aims at developing a *transition theory* that is accepted as an explanation for the observed transition dynamics in general. In the course of such a theory development process, simulation models may serve as tools especially for testing and refinement purposes. Similar potential uses of simulation models are already discussed by several other authors in the context of studying social phenomena (Axelrod 1997a; Hartmann 1996; Kliemt 1996; Nowak and Lewenstein 1996).

When there is a set of assumptions and hypotheses that constitute a theory-to-be, it is generally hard to evaluate the proposed theory either due to its imprecise/incomplete nature, or due to difficulty in understanding the dynamic consequences of the individual assumptions when considered concurrently. In these cases, it is possible to test these theories ‘formally’ using a model built based on the premises, assumptions and hypotheses that constitute the theory. Even though the main contribution of a model is to provide a temporal behaviour under the given assumptions and hypotheses, sometimes just the modelling process itself may work as a debugging stage for a theory without even running the model. This way the model serves to identify the imprecise/incomplete parts, which would be hard to identify when it is stated in a non-structured and informal manner. A theory should be formally described if it is to be incorporated into a model. In that respect, during the modelling process, the theory has to be made explicit, and this clarification sometimes may lead to identification of some inconsistencies and voids in the elements, assumptions and/or claims of the theory. Apart from that, it is also possible to identify some ‘conceptual voids’ that have to be specified in order to make the explanation complete. Leaving these diagnostic benefits of the model-building process aside, models are claimed to be good candidates of a formal language for these theories, since they are *formulated in a precise way and thus their content is at least inter-subjectively accessible* (Kliemt 1996).

Upon completion, a simulation model constitutes a synthetic system that behaves as by the theory. Hence, the simulation runs based on this model will provide some sort of *synthetic* empirical data, which in turn can be compared to the expected behaviour according to the theory, or to the empirical data on hand regarding the real dynamic phenomenon under scrutiny. A possible outcome of such a comparison may show that the proposed theory fails to explain the process. In other words, the relationships, mechanisms, or elements in the proposed explanation do not yield the dynamic phenomena of interest: the model falsifies the proposed explanation. This constitutes the biggest strength of a model when it is used for theory testing purposes. Once the conversion from the conceptual explanation to the formal model is done in an appropriate way, the conclusion reached indicates that even with the assumptions of the
provided explanation, it is not possible to replicate the dynamic phenomenon being studied. Such a conclusion either leads to the abandonment of the explanation, or its re-construction and refinement.

In other cases, the researcher may 'fail to reject' the provided explanation based on the model output, which is the case when the model generates a dynamic behaviour at some degree similar to the dynamic phenomenon being studied. Then, the model can further be utilized in order to refine the theory/explanation, by experimenting with some assumptions; adding new ones, removing some of the existing ones and redefining others. The refinement process mentioned here does not necessarily mean addition of new components to the theory. Observing that the set of assumptions regarding the process results in a good explanation does not indicate that all of the constituents of the theory are important with respect to the explanation of the process. It may also be possible to identify the core of the theory during this experimentation process. Detecting those redundant components (i.e. insignificant for the observed dynamic behaviour) in the explanation in turn results in a simpler theory having the same explanatory power.

It is possible to identify several studies using models in this sense in transition studies. A recent example is de Haan's work (2008). This model relies on a conceptualization based on the transition theory, which locates the regime and niche concepts introduced in this theory at the core of the model (Geels 2002a; Geels 2005c; Rotmans 2005). Transitions are seen as a sort of power struggle between the incumbent regime and the emerging niches in this model. The abstract model based on a set of partial differential equations represents the basic characteristics of these regimes and niches, as well as the proposed interactions among them. Although it is not the primary objective of the author, the experiments conducted with the model show to what extent this conceptualization may lead to the previously observed common transition patterns. In the way Schilperoord et al. (2008) use their model, it is possible to recognize both the theory testing and development aspects. The model they discuss is a general model that is developed as a proof-of-concept for a modelling framework designed for studying transitions (Haxeltine, Whitmarsh et al. 2008). The primary purpose of the model is to demonstrate that the proposed elements and mechanisms in the framework are rich enough to capture the essential aspects of transition dynamics; hence suitable for studying specific transition problems. However, the experiments conducted with the model lead to a new idea, i.e. 'agent transformation', that is important in explaining some processes. In a sense the model-based testing and theory refinement proceed in a recursive manner as seen here. Timmermans (2008) also uses his model for similar purposes. Characterizing transitions as a sort of radical change, Timmermans aims to establish a formal link between the transitional change and the punctuated equilibrium phenomenon. In doing so, Timmermans looks for a simple configuration of actors that leads to a punctuated equilibrium phenomenon. By linking back this setting to the transition context, Timmermans aims to establish an explanation for the abrupt nature of change in transitions, or what might be causing it.

Considering the different forms of simulation-supported analysis, and different challenges regarding understanding transition dynamics; we identified the aforementioned three model-use schemes as the most relevant ones in the context of transition studies. The first type differs clearly from the latter two, especially due to its heavy reliance on empirical data related to a particular real-life problem context. The latter two model-uses are relatively more similar to
each other. This similarity is primarily due to such models being generic and having loose correspondence with some particular real-life systems. Despite this similarity, the difference between these two model-uses lies mainly in what is being investigated: in the case of generic insight development, the relationships and processes that are included in the model are taken for granted, and it is the set of dynamic phenomena that can be generated by these which is the subject of enquiry. In the case of theory development, the dynamic phenomenon is taken for granted, and the sufficiency of a set of proposed processes in generating this particular phenomenon is investigated.

Although we do not rule out potential contributions of the simulation-supported approach in other forms, the aforementioned three uses are likely to be the most expedient ones. Distinguishing such different uses is very important for clarifying how can the approach be used for transition studies, which is one of the research objectives of this study. Moreover, a set of points related to the overall contribution of this preliminary model-use typology is worth being highlighted.

First of all, simulation-supported analyses are generally associated with the first type of model-use. This implicit association shapes methodological discussions, and the latter two types of uses have been overlooked. This leads to an underestimation of the potential contribution of the simulation-supported analysis approach in studying transition dynamics. Secondly, these three types of model-uses have very different requirements, merits, and shortcomings. For example, empirical data needs, or validation requirements differ for simulation models to serve different uses. Therefore, such a typology is crucial for the accuracy and lucidity of methodological considerations. Thirdly, the typology provides valuable guidance for the following parts of this study that are on developing a general conceptual framework to be used in developing simulation models. Since the content and scope of a model is dependent on the objectives that the model will serve, this typology provides an important input for the conceptual framework development process by explicitly distinguishing major objectives.

Although the typology addresses the ‘in which ways…?’ question on the utilization of the simulation-supported analysis, the ‘to what extent…?’ question still needs to be addressed. The following section will focus on this issue by discussing major issues that limit the extent of use of the approach, and which are serious challenges.

### 2.4. Challenges in simulation-supported analyses of transition dynamics

As is the case with any analytical approach, simulation-supported analysis is not free from shortcomings that limit its extent of use. Ignoring these shortcomings can naturally yield misleading results, which in turn result in discrediting the analyst and the approach. In this section, we discuss those shortcomings, and related methodological challenges, when the approach is considered in the context of analyzing transitional change in socio-technical systems. These challenges also indicate some directions of methodological progress needed in the field. The main shortcomings and related challenges regarding the approach stem from three major issues; modelling the social, capturing the novelty, and role of contingencies.

Naturally, any model aiming to study socio-technical transitions incorporates some components corresponding to the social domain. However, in the current state of the social sciences, a commonly accepted depiction of the way individuals or social systems behave
is lacking. This issue is not just about not possessing that depiction, yet, but it is also about possible impossibility of having such a clear-cut depiction. Additionally, social components of a socio-technical system differ from other components, such as purely techno-physical ones, in the sense that the social ones are adaptive and have the capacity to reflect. It might be possible to represent the way a societal system behaves under current conditions in a satisfactory way. However, in the face of changing external conditions, policy interventions, and/or innovations, the societal system may go through a radical re-structuration that makes the former representation of the system obsolete and invalid. This can be due to social actors developing (inventing) new behaviour patterns, altering their decision heuristics, or building up new social interactions. Alternatively, it can also be related to ‘sleeping structures’, which can be characterized as behaviour routines or social interactions that are not active under normal conditions. These may be activated during unusual periods, such as transitions. The adaptive nature of social elements and sleeping structures make modelling the social even a more a serious challenge in the context of transitions.

Broadly, two ways of dealing with the adaptive nature of the social components can be discussed. The first way is to embed probable alternatives (i.e. room for change), for example in the form of alternative decision heuristics or action rules, into the model ex ante. This requires the identification of possible alternatives, or structural scenarios that go beyond simple parameter changes in the models. Such an effort is rarely necessary in conventional model-based studies, since the configuration of the real system is assumed to stay intact during the time horizon of the analysis. This is rarely a valid assumption in transition studies. Therefore, the identification of possible system configurations constitutes an important issue to be considered as a natural part of the modelling process. Incorporating these possible alternatives provide room-for-change into the structure of the model. However, it does not solve the problem completely, since it is not possible (or at least practical) to foresee and cover all such alternatives. Therefore, it would be misleading to expect these models to generate predictions on future behaviour of socio-technical systems going through a transitional period. In fact, we consider predictive attempts with simulation models in the context of transitions to be seriously flawed at a very fundamental level, and, therefore, exclude such use from the typology discussed in the previous section. Despite this limitation, simulation models can provide very important insights about the conditions and dynamics that would make it more or less likely for a system to go towards a certain direction. Although such insights say little as a forecast for future system configuration, they may tell a lot about, for example, factors inhibiting progress towards desirable configurations (e.g. de-carbonized mobility system).

The second way of dealing with the adaptive nature of the social components is the development of models with evolving2 structures; i.e. models that can endogenously alter their structures. This is possible to a certain extent, but comes with an additional set of issues. The re-configuration of the system can be seen as the endogenous development of new rules, regulations, and relationships within the model. All of these can be considered as social novelties, and, therefore, their endogenous generation by the models can be treated as a sort of capturing the novelty problem, which is second major problem mentioned above.

Capturing the novelty is the second problematic issue for model use in the transition field. By definition the transition problem involves the emergence of a new way of fulfilling a

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2 The term is used in it its literal meaning, rather than its connotation in the biological evolution.
societal function, a new way of system organization, a new artefact to appear, etc. Models can incorporate features that introduce novelty during simulations, such as the case in some evolutionary models. However such features should be utilized with care, and the outcome of such models should not be misinterpreted. The processes according to which novelty arises are path-dependent ones, in other words what is going to emerge as a novelty in the future is dependent on many uncertainties. Therefore, foreseeing which specific novelties will appear in the system can easily be characterized as impossible. In that respect, the output of the models incorporating some sort of ‘innovation’ processes does not carry a forecasting value. The insight to be developed in a credible manner is more about the nature of these innovation processes, rather than the specific novelties they yield. For example, it is possible to develop some understanding about the policies yielding the highest variety of innovations in the system using models. However, using such a model to predict which specific novelty will arise, or to prescribe conditions that will yield the emergence of a specific novelty should be questioned thoroughly in terms of credibility.

The role of contingencies in shaping the behaviour of a socio-technical system is a major one, since contingencies are important both in the adaptation of the social components, and in the emergence of novelties, since they are both path-dependent processes. The contingencies are important, and, by definition, unforeseeable (e.g. in timing, or scale) developments. A ‘foreseen contingency’ constitutes an oxymoron as a concept, and in that respect, it is not possible to endogenously capture the emergence of contingencies in models. Therefore, it is not the emergence of a contingency, but the system’s possible behaviours following the emergence of a contingency are what should and could be analyzed via simulation-supported analyses. Gunnar Myrdal, a Nobel laureate economist, makes a remark along the similar lines with what is discussed above;

“The main scientific task is … to analyze the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its internal processes.” (Myrdal 1957, p. 18)

These three major challenges have different implications on different types of model-use, as we have also highlighted in the previous section. When we consider these implications separately, it is seen that the approach is still a promising one, despite the aforementioned shortcomings. In cases of model-use for generic insight development, and model-use for theory development the implications are limited. This is primarily due to the loose correspondence of models that are used for such purposes with a particular real-world system. When a simulation model is used for generic insight development, the subject is a dynamic process (or a set of them) in its generic form. This can be an empirically observed, and/or theoretically proposed process. Such a model clearly has no claim of mimicking a real-world system, or of generating some predictions; the scope is limited to analyzing the dynamic behaviour generated by the process under different conditions. Additionally, since the objective is to study the process in its proposed (or observed) form, future changes in the (social) process are irrelevant, and out of scope in such studies3. Finally, the empirical and/or theoretical evidence about the process of concern constitutes the basis for validation of models used for generic insight development, which is not a problematic issue.

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3 This does not imply that the analyst rules out such future changes. They are simply left out of scope.
The case of model-use for theory development is also very similar to the case discussed above. In this case, the subject being modelled and analyzed is a theory with its constituent assumptions, premises, relationships, processes, etc. It is the theory that the model represents, not a particular socio-technical system. Therefore, as long as the social behaviour, for example, is depicted in a formal and consistent way within the scope of the theory, it does not constitute a problem for a simulation-supported analysis. If this is not the case (i.e. social behaviour is out of the scope of the theory, or the theory fails to depict it properly), capturing the social behaviour is a problem mainly related to the proposed theory, rather than the simulation-based refinement process.

The situation is not the same when simulation models are to be used for case-specific analyses. It should be clear from the issues raised in this chapter that these models are not forecasting tools, and should not be treated as such. The risk of doing exactly this is highest when case-specific models are used for policy-testing and scenario experimentation. The results can easily be understood and communicated as forecasts, which would be misleading. The purpose with these models is to explore the probable set of future dynamics, rather than generating one as the forecast; and to develop insights about probable reactions of the socio-technical system to changes in some conditions. The results should be interpreted as being about internal inertia and tendencies of the system under currently foreseeable conditions, rather than expected precise time-trajectories. This point can be clarified on the example of an airliner pilot training simulator: none of the simulated flights in any flight simulator can exactly replicate a particular flight for a given destination, and this is not the purpose of the flight simulator. The simulator is used to enhance the understanding of the pilot trainee on the interaction of multiple dynamics regarding the plane and the weather conditions. This is exactly what should be aimed at in using simulation-supported analysis for case-specific insight development purposes.

However, considering the deep uncertainty about socio-technical systems that partially stems from the nature of social components, emerging innovations, and contingencies, exploring the dynamics of these systems is not straightforward. In that sense, traditional scenario analysis, which is mainly based on a limited number of runs with various parameter values, may not be appropriate. Considering the uncertainty in the systems under transition, the exploration should cover a wide range of variations, including not just variations in model variables, but also in model structures used to represent some aspects of the system. At the end, the interpretation of the results should also be consistent with the logic behind this mode of usage. Novel approaches that address the needs of such simulation-based experimentations, such as exploratory modelling and analysis (EMA) have already been proposed (Agusdinata 2008; Lempert et al. 2003; Pruyt and Hamarat 2010). Adoption of this kind of novel analysis perspective seems to be critical for getting the most out of simulation-supported analysis in an appropriate manner in analyzing transition dynamics.

2.5. Conclusions

In this chapter, we have discussed simulation-supported analysis as an approach for studying transition dynamics, and, especially, drivers of these dynamics. In doing so, we primarily consider the main characteristics of the transition dynamics field, which are shaped by the basic assumptions and major objectives in the field. The focus on system behaviour between
two equilibrium states of the system, rather than the equilibrium states, is one of these defining characteristics. Based on the assumption that these equilibrium states are consequences of path-dependent developments, predictive or prescriptive efforts related to such states are of no relevance in the field. Rather, a descriptive/explanatory stance is dominant, and the emphasis is on understanding the way dynamic behaviour of the system is shaped along the transition process. This descriptive/explanatory stance towards dynamic system behaviour brings about a natural fit between the problem and the simulation-supported analysis approach. Furthermore, the systems considered in the transition dynamics field demonstrate dynamic complexity, which is beyond straightforward intuition. This makes simulation-supported analysis an appropriate approach for analyzing transition dynamics, and probably one of the most important approaches that is required in the toolbox of the transition scholars to achieve progress in understanding these complex transitional change processes.

When we investigate some relevant subject fields that can be considered as the progenitors of the transition dynamics field (i.e. diffusion studies, integrated assessment, evolutionary economics, and complexity theory), we also find supporting evidence for our conclusions regarding the potential role of simulation-supported analyses. In these fields that tackle problems that are somehow similar to the ones considered in the transition field in character, the simulation-supported analysis approach seems to have an established position as the primary approach to attack the question at hand.

As summarized above, simulation-supported analysis is discussed as a promising approach in the context of transition dynamics. Despite sharing main methodological aspects, such analyses can be conducted in a variety of forms in order to serve different type of objectives. In that respect, we discuss three (simulation) model-use types that we consider as most relevant for transition studies. In model-use for case-specific insight development, the aim is to develop some understanding about plausible dynamics of a particular real-world system under different conditions (scenarios). In model-use for generic insight development, it is a set of generic dynamic processes that are of interest rather than a particular real-world system; the models are used to explore dynamic consequences of these processes under various conditions. In model-use for theory development, models serve as a formalized expression of a proposed theory. By forcing formalization, the models help to identify inconsistencies and voids in the theory. More importantly, they enable evaluating whether the premises of the proposed theory lead to the dynamic consequences, as claimed in the theory. Explicit recognition of these three model-use types is important both to see the potential contribution of the approach better, and to discuss the shortcomings in a more precise manner since these shortcomings are dependent on the purpose a model serves in a simulation-supported analysis.

In the last section of the chapter, we focus on the major challenges in using simulation-based analysis in the context of transition processes. The challenges are mainly related to modelling the social, capturing the novelty, and the role of contingencies along the transition process. We investigate the impact of these challenges for all three different model-use types mentioned above, and conclude that their impact on the model-use for general insight development, and model-use for theory development is minimal. This is mainly a consequence of this type of modelling studies’ loose connections with particular real-life systems, and the absence of a one-to-one correspondence claim with a real-life system’s behaviour. On the other hand,
these challenges impose important constraints on the nature of valid conclusions that can be drawn when models are used for *case-specific insight development*. Conclusions that are in the form of predictions and forecasts related to a system in transition are difficult to defend with respect to their validity considering the aforementioned challenges. This can be considered as a serious limitation of the approach. However, as tools for exploring dynamic consequences of the internal processes of the target system, these models have potential for developing insights on dynamics and underlying processes. Besides, the limitations posed by the aforementioned challenges can be reduced via using novel experimentation schemes, and developing models with room for structural change.
Different Approaches to Modelling Transitions

3.1. Introduction

The previous section primarily focused on how simulation models can be used for analyzing transition dynamics. An equally important issue is related to the development of these simulation models for analyzing transition dynamics. In order to address the issue, we review a set of established modelling paradigms used for analyzing socio-economical phenomena. These paradigms, i.e. econometrics, micro-simulation, system dynamics, and agent-based modelling are discussed with their differing technical and conceptual perspectives in the following sections.

3.2. General overview of modelling paradigms

Although there are already specific examples of model-based research in the transition studies field, it would be misleading to consider the current state-of-the-art as mature. Therefore, the larger set of approaches that can potentially be relevant for model-based transition studies is considered in this section, rather than the more limited set of modelling approaches that have already been used. In that respect, approaches that have been used for studying socio-economical systems with the help of quantitative models and simulation are reviewed, and four prominent approaches are identified: econometrics, micro-simulation\(^1\), system dynamics (SD), and agent-based modelling (ABM). Among these, the former two have not been utilized in the context of transitions so far, and the possible extent of their contribution is unlikely. This evaluation is based on fundamental assumptions and dominant perspectives in these two approaches (i.e. econometrics and micro-simulation), and is elaborated in the following paragraphs.

An econometric model can be characterized as a set of theoretically grounded, and empirically quantified quasi-causal relationships that represent a target economical system

\(^1\) The term, as it is used in this text, refers to microsimulations in the domain of economics. There is another strand of models known also as microsimulations, which deal with traffic flow and urban development problems (Algers, Bernauer et al. 1997; Cetin, Nagel et al. 2002). Those are considered as agent-based model examples due to the proximity in perspective and implementation.
(Meadows and Robinson 1985). These models are generally used for structural analysis, policy design and forecasting purposes. Some of these models can be solved analytically, but for others simulation is needed to numerically solve the model due to the high complexity that makes the model analytically intractable. The dominant purpose in econometric models can be summarized as short-term prediction/forecasting of aggregate economic variables. Therefore, numeric precision is of the utmost importance, and statistical verification of the model parameters based on extensive historical data is a defining characteristic. Being this dependent on historical data implicitly brings about the assumption that the set of relationships in the target system will be the same as the ones pertained during the historical period from which the model parameters are estimated. In other words, this type of models is too rigidly tied to the past behaviours to be suitable for studying the response of the system to, for example, totally new policies, or to the introduction of radical innovations.

Micro-simulation models share most of the fundamental characteristics of the econometric models, but differ significantly regarding the aggregation issue. Broadly, the primary objective of a micro-simulation model is to analyze and forecast the individual impacts of economic and social policies, such as tax and pension policies, on the distribution of key aspects, such as income (Merz 1991; Orcutt et al. 1986). The emphasis on the distribution draws the attention to the individual-level heterogeneity, and determines the defining characteristic of the approach; depiction of the socio-economical system in terms of its micro elements - be they individuals or firms- using very large samples or even with 1-to-1 mapping to represent the real system. This micro-level focus differentiates the approach from econometrics, which employs a more aggregate perspective. However, as in the case of econometrics, the dominant purpose is forecasting, and the micro-simulation models are developed based on extensive historical data sets at the resolution level of the individuals, such as census data. The level of detail of these models brings a significant computational burden, as well as problems in communicating model structure and results (Zaidi and Rake 2001).

Despite differences between these two approaches, the issues that make a significant contribution of micro-simulation and econometric models in the transition field unlikely are common to both. Above all, both econometrics and micro-simulation are characterized by a similar overall objective, which is to forecast policy implications in the prevailing system structure. In that respect, exploration of conditions and relationships that significantly differ from the historical ones is not a strong point of these approaches. Additionally, development of generic models for exploration is not a common practice, if acceptable at all, within both approaches due to the heavy reliance on detailed historical data to formalize these models. Since equations used in these models are quasi-causal in nature, and are mainly inspired from economical theory, it is not easy to incorporate cases that go beyond fundamental economical assumptions, such as the rationality of the actors or perfect information. Eventually, these characteristics constrain the potential use of econometric and micro-simulation models only to one of the three model uses discussed before; i.e. case-specific insight development. Even for case-specific insight development purposes, the short-term forecasting emphasis and the high importance of numeric precision observed in these approaches do not fit well with the long-term emphasis and importance of behaviour patterns in transition studies. Furthermore, the implicit assumption that the historical system relationships will prevail during the time horizon of the analysis is an important misfit when the phenomenon of interest is a system transition. In conclusion, despite acknowledging their potential
appropriateness in conducting short-term economic policy analysis, these two approaches are not expected to establish a place among the model-supported transition studies.

The potential fit of the other two approaches, i.e. SD and ABM, is visible even just considering their utilization levels in the current state of model-supported transition studies. Both ABM and SD are subject-field independent approaches that aim to analyze dynamic phenomena especially in socio-economic systems. In general, they avoid a predictive or prescriptive stance, and adopt a more descriptive one; they aim to understand dynamic phenomena via depicting the way components of the related system interact and change over time in the form of a model, and analyze this model’s behaviour via simulation experiments. These aspects overlap with the dominant perspective in the transition field, and this makes both approaches, and also the others that may evolve out of these two, strong candidates to dominate quantitative transition analyses. Therefore, these two approaches are discussed further in detail in the following sub-sections. During this discussion, we aim to clarify if any of these approaches methodologically fit the task of analyzing transition dynamics better. In that respect, we mainly focus on the differences of these two approaches. When it comes to differences between these two paradigms, major issues seem to be related to the dominant conceptual perspectives. Therefore, we especially focus on how these differences relate to the perspectives within the transition studies domain, and aim to highlight the issues that are relevant for methodological choices in simulation-supported analyses on transition dynamics.

Before proceeding into the detailed review of SD and ABM, we introduce a preliminary categorization in the following section for the conceptual perspectives used in developing models in these two paradigms. Such a categorization will be used to structure our review of these two approaches, especially from a conceptual point of view.

### 3.3. Categorizing conceptual perspectives in simulation modelling

Any modelling paradigm imposes, implicitly or explicitly, a conceptual frame that conditions the way we look at the target system, and what we focus on as the sources of dynamic behaviour. In order to structure a methodological review from a conceptual point of view, we categorized the used conceptual frames with respect to two properties, and developed a four-type categorization of the conceptual frames used in simulation modelling, in general (Figure 3.1).

![Figure 3.1. A model classification framework based on level of analysis and drivers of behaviour](image)
The first of these properties is the level of analysis. It is possible to analyze a system at a multitude of levels, which are not ontological, but epistemological. In the simplest of the dichotomies about this matter, it is possible to recognize a macro and a micro level, which are relative to a given phenomena of interest. A macro-level analysis is conducted at the level of the dynamic phenomena under scrutiny, whereas a micro-level analysis focuses on the individual elements of the system encompassing the phenomena of interest. Motorway jams, as an example of dynamic phenomena of interest, may be analyzed treating the traffic as a sort of liquid flow, and focusing on factors such as the mean flow speed on the main arteries, and in- and outflows from connection roads. Alternatively, the elements of the traffic system, i.e. vehicles, can also be the unit of analysis; then the analysis relies on issues such as the individual speeding and braking behaviour, and inter-vehicle distance. As should be clear, the former case corresponds to a macro-level analysis, whereas the latter fits into the micro-level analysis class.

The second property is about the main driver of system behaviour in the model. A simulation model generates a temporal system behaviour by means of changes in its elements. It is possible to conceptualize such changes as a set of continuous processes, or relations between the model elements; e.g. distance kept between vehicles increases as the driving speed increases. Another way to approach the matter is to depict change as set of discrete actions, or events altering the state of the model elements; e.g. driver brakes when the distance from the front vehicle is below a threshold. This introduces a second dichotomy, which is fundamental in distinguishing the two modelling approaches to be discussed; relation-driven vs. action-driven models.

The conjoint outcome of these two dichotomies is a basic classification scheme, which consists of four quadrants (Figure 3.1). In the following sections, this categorization is used as a guide while both reviewing the general characteristics of the two modelling approaches (i.e. SD and ABM), as well as discussing specific modelling applications, especially on the transition dynamics subject.

3.4. System dynamics (SD)

The SD approach can be characterized as an equation-based modelling approach, since the model description is composed of a set of differential equations. In this approach, the change in the variables that represent the system state is described via functional relationships between these variables, which represent the causal (or quasi-causal) dependencies. This way, the behavioural mechanism that determines the model behaviour over time is composed of chains of functional relationships that link the system variables to each other. Therefore, the SD models are relation-driven simulation models according to the classification introduced before.

Since open chains of relations are not capable of generating complex dynamics, the analysts using this approach naturally focus on the closed chains, i.e. feedback loops, while they are aiming to investigate the system behaviour. This constitutes one of the defining characteristics of the SD approach. Leaving the technical aspects aside, an analyst using the SD approach hypothesizes, implicitly or explicitly, that the behaviour of the system is conditioned mainly

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2 In a feedback loop, a change in a variable propagates along the loop through other variables, and consequently reaches the initial variable, influencing subsequent changes of that variable.
by feedback loops in the system, and time delays in these feedback loops. This feedback focus is apparent in the way the SD models are used. During the simulation experiments, the emphasis is on weakening/strengthening, and/or speeding-up/slowing-down the major feedback loops identified in the system. When it comes to the analysis of the system behaviour, the ultimate goal is to link the observed behaviour back to the model structure. In other words, an important part of the SD approach is to identify an explanation for the behaviour in terms of the feedback loops included in the model. A more comprehensive review of the SD approach can be found in (Sterman 2000).

One of the main aspects used to characterize the SD approach is its aggregate focus (Gilbert and Troitzsch 2005; Schieritz and Milling 2003). However, it is possible to distinguish two fundamentally different types of aggregate focus. The first one fits into the macro-level focus class mentioned in Section 3.3. In this perspective, it is assumed that a system (e.g. a socio-technical system) can be described and studied via system-level concepts and relationships. These concepts (e.g. income distribution) and relationships (e.g. uneven distribution increasing crime rate) are emergent ones, which are claimed to exist based on empirical and/or theoretical data. These relationships emerge as a consequence of the micro-level elements’ collective behaviours. Based on such a perspective, SD models with macro-level focus are disassociated from the micro-level elements of the system. For example, some of the renowned models in the field like WORLD-2 (Forrester 1971) and WORLD-3 (Meadows, Meadows et al. 1972; Meadows et al. 1974), are examples of models developed with such a perspective. Despite being rare, it is also possible to recognize a set of modelling studies in the transition field that can be characterized by this structure-focused perspective. For example, de Haan (2008) uses a conceptualization commonly used in the transition field, and represents a transition process as a power struggle between a regime and niches in his partial differential equation model. According to this conceptualization, the regime represents the dominant set of actors, practices, values, institutions and artefacts in the societal system, whereas the niche represents the novel upcoming one. In this conceptualization regime and niche are assumed to be autonomous from the individual level, and to possess properties like power and objectives of their own. This disassociation from the individual level qualifies this work as an example of this category. Although it is not a SD model, being an equation-based model it has significant similarities with this type of SD models, and can be considered in this cluster.

The alternative approach is the micro-level one. In these SD (or equation-based) models, the variables or processes depicted in the model are based on micro level, rather than being emergent ones. Sterman’s models on inventory oscillations along supply-chains can be considered in this class (Sterman 2000); the dynamic phenomena is studied focusing on the elements that constitute the supply chain system, i.e. individual actors like wholesalers and retailers operating in the chain. Further examples related to transitions can clarify it further; Struben’s work (Struben 2006; Struben and Sterman 2008) can be classified as an example of this type. The focus is on the individual’s vehicle choice as the driver of a mobility transition, and the model relies on individual choice theory. However, what is represented in the model is a group of individuals as one single actor instead of all individuals represented as such. In order to clarify the difference between these two approaches, it can be said that in this latter perspective the models are generally built upon theories and empirical data on the individual level.
The aggregation issue in SD models is very important; once justified, aggregation is a very effective means of simplification, which is a fundamental quality sought for in developing a model. Therefore, a proper aggregate model is, in general, simpler to communicate and less complicated to analyze compared to a disaggregated one that has a higher 1-to-1 resemblance to the real system. This is a very important merit of a model, especially when linking the model structure to the observed behaviour is an important objective, as in the case of any study seeking an explanation for system behaviour rather than a forecast of future behaviour.

Unless used properly, aggregation as a way of simplification may turn into a means of ignorance, and important sources of complex behaviour may be lost during aggregation. This constitutes one of the important criticisms towards SD. However, under some conditions the aggregation does not lead to any loss of dynamic richness in the model, and it can be justified. Justification of the aggregation is dependent on the degree of heterogeneity of individual system components being aggregated, and on the importance of this heterogeneity for the overall dynamics of the system. If it can be assumed that diffusion of material and information is rapid compared to the time frame of the process being studied, it can be argued that components can be treated as homogenous and aggregated without any complications. Therefore, carefully studying the heterogeneity issue regarding the process being studied plays a crucial role in the success of this type of models. However, in cases where aggregation cannot be justified in terms of the dynamic behaviour loss, the appropriateness of the approach to the problem should be considered seriously.

Furthermore, SD models can be considered to have static structures in the sense that model structure (feedback loops, individual relationships between model variables, etc.) does not evolve during a simulation run. Transitions being all about significant change in socio-technical systems’ structure, this constitutes a certain problem-approach misfit. This issue is about, in general terms, capturing the novelty in the system structure, and has already been discussed in the previous section as a major challenge in model-use in the transition field.

3.5. **Agent-based Modelling (ABM)**

Compared to the SD models, agent-based models may be considered as a younger class of models that became especially popular in parallel to the popularity of the complexity perspective in various fields (Coveney and Highfield 1995; Waldrop 1993). As can be easily inferred from the name, in this type of model the system of concern is represented by a set of agents, whose behaviours and interactions drive the system’s behaviour. This way, the change in the system state is conceptualized to take place as a consequence of discrete actions of the agents, or events related to the system variables, which qualifies the approach as an action-based one. An agent in this type of model can be seen as an autonomous body, which possesses a knowledge/information base, a set of action routines, and a controller. Based on the direct interaction with other agents, the observation of the actions of the other agents, or the observation of the environment, these agents update their knowledge/information base. The controller can be seen as the decision engine, which determines which action is to be activated based on the current state of the knowledge/information. As can be understood

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3 Although it is technically possible to develop SD models with evolving structures, as in the case of Duggan (2008), this does not go beyond technical feasibility demonstrations in the SD field.
4 Cellular automata (CA) models (Wolfram 1986) are considered as a special sub-class of agent-based models in this text, since cells can be treated as spatially fixed agents acting based on their neighbors’ states.
from the characterization, the action/interaction routines of the agents constitute the most important aspect of the model in terms of determining the dynamic behaviour. Similar to the SD case, the reflection of this fact is apparent in the model usage stages: analysts design the experimentation process mainly based on these action routines, and also aim to relate the observed dynamics back to the agent behaviour.

The depiction given above is common to most agent-based models. What varies significantly among the models is the definition of an agent; what does an agent represent? An agent can be an individual, a group of individuals, an institution, a nation, or a technology. Despite sharing the way they describe the behavioural mechanisms in the system, agent-based models may vary significantly regarding the conceptualization of the system. Related to that, the macro-micro focus dichotomy presents itself also among the agent-based models used for transition studies.

In the *micro-level* focused cases, the transition dynamics are hypothesized to be driven mainly by the choices of micro-level agents of the system, for example, an agent refers to an individual consumer/user, or a firm/organization. Cantono and Silverberg (2009) approach the transition issue as a diffusion problem in their model composed of individual users embedded in a social neighbourhood, and explore the impact of willingness-to-adopt and imitation behaviour on the take-off of an eco-innovation. In their case-based work, Schwarz and Ernst (2009) utilize an agent-based model representing individuals with differing novelty-related characteristics in order to study the possible transitions to a less water-dependent personal hygiene regime. The model by Chappin and Dijkema (2009) chooses individual power generation firms as the agents in their model, which they use to study possible transition paths to a low-carbon power generation system in the Netherlands.

The macro-level focused cases of agent-based models rely heavily on the concepts developed in the field of transition dynamics (e.g. regime, niches, empowered-niches, etc). The fundamental assumption underlying these models is that regime and niche are autonomous from the individual action, and they possess their own objectives, preferences, and power. These agent-based models are very similar to the *macro-level focused* SD models with respect to the used conceptualization. The regime, empowered-niches and niches constitute the agents in this set of models. The transition, as a process of regime shift, is conceptualized as a power struggle between these agents, and the state of the system is represented by the concepts like the number of niches, the level of power they possess, their similarity with the regime in terms of functional aspects, and the strength of the regime. The system state changes over time as a consequence of actions and events like *transformation*, *absorption*, *niche emergence*, and *niche clustering* (Bergman, Haxeltine et al. 2008). In some cases, these models also incorporate a second aggregation level where they simulate the behaviour of important micro-level agents. In these models, some aspects of the aggregate agents (i.e. regime, niche, etc.), like power, are influenced by the actions of the agents representing individual consumers. As mentioned before, Whitmarsh and Nykvist (2008) uses an agent-based model based on this transition-specific conceptualization in order to study the implications of certain policies on a mobility transition in UK. The models discussed in (Bergman, Haxeltine et al. 2008; Schilperoord, Rotmans et al. 2008) also use the same conceptual framework while developing their agent-based models. This strand of models focuses on the actions/events on the regime-niche level in order to analyze the transition dynamics.
It may sometimes be a very challenging task to formalize a set of aggregate elements and relationships between them in order to explain the dynamic behaviour, especially in the systems composed of individual elements that are highly adaptive in their behaviour. This may be problematic in two ways. In the first case, the researcher may have no knowledge about system-level description, but may be able to observe and imitate the behaviour of individual components. In this case, the only plausible option will be ‘to grow the phenomena being studied from bottom-up’ (Epstein and Axtell 1996); simulating the individual components’ interactions via agent-based models and let the dynamics of the model emerge. In the second case, the researcher may have an initial aggregate representation, which represents the initial structure of the system. However, due to the adaptive nature of the individual components and the co-evolution of their behaviours, the initial aggregate representation may lose its validity and needs to be updated. Unless the researcher is able to represent this co-evolution process in aggregate terms, or foresee probable update requirements in the aggregate system representation and pre-build them, the aggregate representation will fail to capture the dynamics of the system. These two cases (no aggregate knowledge and evolving aggregate representation) seem to be the ones, which agent-based models fit best as models to study dynamics of the system.

This approach also has certain drawbacks and limitations. The first of these aspects is that the internal complexity of agent-based models may easily reach a level that makes it almost impossible for a researcher to deduce any understanding from the simulations. It can be said that in these cases, the model itself becomes too complex. Although the risk of ending up with a too complex model exists for all modelling approaches, the risk is much higher in agent-based models. This risk has already been pointed out by many other researchers indicating that in order to utilize AB models in an efficient way, the model should be very simple and should include only the minimal set of components that is capable of reproducing dynamics of the system of concern (Axelrod 1997a; Epstein and Axtell 1996).

The ability to capture emergent system properties by focusing on individual components and mechanisms (e.g. how these components act under certain circumstances) is mentioned as the most important advantage of agent-based models. However, this aspect of the approach also causes serious and hard to avoid complications in terms of validating the models constructed. As mentioned before, the way these models are used in the field of complexity aims to identify a minimal set of mechanisms that can reproduce the complex system level behaviour. A problem is that this minimal set is not unique. In other words, mapping between the mechanism sets and the system behaviour is not one-to-one, but many-to-one. Hence, it can be a serious challenge for the researcher to validate his choice of individual components and mechanisms in capturing the dynamics of the system.

The ABM approach allows for the development of simulation models with a dynamic structure. These models incorporate meta-behaviour routines, which depict how an agent can invent new behaviour rules, and modify its behaviour structure endogenously, and may start acting according to the rules not directly implemented by the analyst. Despite being feasible, such implementations are rare, mainly due to the fact that the evolution of the agents becomes too complex to distil any insight from them. In short, the approach provides the possibility of developing evolving models, but utilization of this possibility is not straightforward, and easy. Such extensions may yield very interesting and complex phenomena, but linking these back
to the actual transition problem at hand, and distilling insights can be hard to achieve. Hence, novel ways of tracking down the underlying reasons for the observed system behaviour for such models are required in order to benefit from such flexibility offered in the ABM approach.

3.6. Conclusions

After reviewing four prominent approaches, this chapter mainly focuses on two modelling approaches; i.e. SD and ABM. An overview of the main characteristics of these two approaches is provided above. In doing that, we refrain from passing any judgment about which of these two approaches is ‘better’ in studying transitions. Considering the multi-dimensional nature of the transition problem, and the variety of potential uses of models within this context, it would be misleading to assume a single approach as the magic bullet. Similarly, it is hard to speak about a single comprehensive model to study all aspects of transitions. Therefore, each effort in the field focuses on a subset of those dimensions of transitions, and this subset is an important determinant in the approach choice. Independent of this choice, it will be a fallacy to talk about the fit of a particular approach. Secondly, three different uses of models in transition studies were discussed previously in Chapter 2, and different uses have very different needs in terms of what a model should cover and deliver. Hence, it is misleading to make a general statement about which approach works better in transition studies. An approach/method choice preceding a detailed specification of the purpose and the perspective (i.e. premature method choice) is a poor practice in general; since such an early choice also conditions the way the analysts perceive the system and the problem.

Furthermore, the problem at hand is a complex phenomenon that operates at multiple time scales, is rich in feedback and driven by heterogeneous systems actors. In that respect, the problem demands the strengths of both approaches in particular cases. Gathering the strengths of these approaches may be achieved in multiple ways. One way of doing this is the coupled usage of multiple models. For example, Yücel and van Daalen use an agent-based model to analyze the impact of social network structure on information diffusion, and later these insights are incorporated into a simpler SD model on the broader ‘innovation diffusion’ problem (Yücel and van Daalen 2009c). Another way is to explicitly integrate such models into hybrid models, where macro level regularities are represented in the conventional SD way, and interact with an agent-based depiction of the micro level processes. Pros and cons of such an approach are discussed elsewhere by Yücel and Meza (2007). The model to be discussed in Chapter 10 of this dissertation (i.e. ElectTrans) can also be considered as an example of such hybrid models. In conclusion, when it comes to understanding transition processes, the methodological choice is more about in which way to combine the strengths of these two approaches, rather than making a discrete choice among them. This way it is possible to overcome the problem of failing to capture the essence of the dynamic problem at hand mainly due to being conditioned by the methodological perspectives.
The Actor-Option Framework

As already discussed, one of the primary objectives of this study is to develop a general conceptual framework for simulation-supported analysis of dynamics of change in socio-technical systems. The outcome of the efforts towards this objective is the actor-option framework, which constitutes the main subject of the second part of the dissertation.

Before proceeding into the chapters that constitute Part II, we elaborate on our motivation for developing such a general framework, and also on the approach we used during the development process in the following two sections. Following these, Chapter 4 introduces the main concepts of the framework, and the general frame that depicts the way these concepts are interrelated, and interact. Chapter 5 elaborates further on the nature of these interactions, and discusses a set of general mechanisms of change. Before concluding Part II, we position the actor-option framework in the transition studies field by discussing its relation with, and differences from the existing contributions with similar objectives.

a. Motivation and objectives

Besides conducting case-specific analyses, an important objective of the transition dynamics field is to develop a general understanding about transitional change processes. In aiming for such an objective, the implicit assumption of the scholars is the presence of some level of similarity among transitional changes across specific cases, and also domains. This similarity is not just in the characteristics of the observed dynamics (i.e. behavioural similarity), but also in the underlying processes and system configurations (i.e. structural similarity).

First of all, developing such a general understanding demands a set of analyses crossing the boundaries of any individual case, and even the boundaries of individual domains, such as energy, mobility, and health. However, in the absence of concepts that correspond to the aforementioned similarities in behaviour and structure, it is not easy to do so. Transferring the
insights developed in one domain to another, or using case-specific findings for enhancing the
general insights on transition dynamics require a general conceptual language that addresses
similarities among socio-technical systems with respect to transitional change processes. The
perspective that provides the motivation for developing the actor-option framework is very
similar to what Moss and Edmonds discuss in the context of social sciences;

“Rather than looking only for special reasons to account for unpredictable and clustered
volatility in each type of social institution, we find it natural to investigate whether there
is any element of generality in the generation of these unpredictable phenomena.” (Moss
and Edmonds 2005)

Secondly, the aimed understanding about transition dynamics is mainly related to factors and
processes that drive and influence these dynamics. In other words, we aim to explain transition
dynamics in terms of their drivers in the corresponding socio-technical system. For this, a
conceptual representation of the structural similarities (e.g. common system configurations,
common dynamic processes) among socio-technical systems with respect to transitional changes is necessary. Therefore, the aforementioned general conceptual framework should be explanatory in nature. In other words, the framework should incorporate a set of general elements and processes in the context of socio-technical systems that can be used to construct explanatory models for transitional changes. In that respect, our motivation in developing the actor-option framework shows similarities with the Hedström and Swedberg’s (1998a) sociological approach, which aims to identify and study an ensemble of fundamental mechanisms that can be used for explanatory purposes in a wide range of social situations. In our case, we aim to explain dynamic phenomena in the context of socio-technical transitions. As already discussed in Chapter 1, there is no comprehensive explanatory framework in the current state of the transition dynamics domain.

Thirdly, such a general conceptual framework can supplement simulation-supported analysis by providing the conceptual basis (i.e. conceptual model) for simulation models to be used. This coupling enables focusing on general transition dynamics in simulation experiments, and developing general insights about transitional change processes in socio-technical systems. In that respect having such a general framework is also very important in realizing the potential contribution of the simulation-supported analysis approach discussed in Part I of the dissertation.

The three issues mentioned above constitute the motivation for developing the actor-option framework. The framework is aimed to be a repository of general conceptual elements and processes that can be used to develop explanatory accounts, which can be translated into simulation models, for transition processes in socio-technical systems.

b. Framework development process

As mentioned above, the main objective is to look for elements of generality that explain the
generation of transitional dynamics in the context of socio-technical systems. This requires
generalization via distillation and abstraction. The distillation part is about identifying the
important elements from each transition case. The abstraction is about going beyond the
case-specific circumstances, and formalizing the identified element at a higher abstraction
level so that it is possible to see whether it also applies to other transition cases. The biggest
The challenge about the abstraction is its level: working at the highest abstraction level increases the possibility of finding the same concepts in a large set of cases. However, the explanatory power of elements also deteriorates as they lose their specificity, in other words when their abstraction level gets higher. Hence, the choice of abstraction level involves a trade-off between generalization and explanatory power. Since maintaining the direct link to the policy-relevant issues is an objective of this study, this sets an abstraction limit in this process. The cost of maintaining such a link is a limited claim of generality. In that respect, this study covers a specific domain of application, i.e. transitional change in socio-technical systems. However, the resulting framework is still relevant, possibly with some limitations, for analyzing transitional change processes in different kinds of systems, such as socio-ecological ones.

The distillation is basically an identification and conceptualization process. It is mainly based on induction from case studies, supported by existing theories as the raw input. Although the methodological approach used for framework development is not a full-fledged example of the Grounded Theory Approach (GTA), it is inspired by it and shares important characteristics with it. In that respect, the method used in this study shows significant similarities with the method followed by Mozdzanska (Mozdzanowska and Hansman 2008), and Bijker (1990).

Briefly, GTA can be considered as a method to develop a theory about a phenomenon inductively from a bulk of data, which can be purely qualitative (Glaser and Strauss 1967; Strauss and Corbin 1990). As the initial step of the framework development, comprehensive case studies about historical transitions, and more focused ones on transition-related processes were studied. These cases constituted the raw data used at this stage of the study, which corresponds to the ‘open coding’ stage of GTA. However, different from conducting an open coding process on pure empirical data, the raw data in this case consist of second-order empirical data. In other words, it is interpreted empirical data, in which the perspective of the researcher who has conducted the case study is embedded. This demanded some extra caution in treating these case studies.

The overall development process can be considered as a gradual one: the first cases led to the early forms of the actor-option framework. Later, as new cases from the literature are analyzed, the framework is enhanced by introducing new concepts, and by refining the existing ones. During this process, we rely on two different clusters of case studies from the literature. The first cluster (i.e. transition cases) corresponds to cases on system-wide structural changes, which discuss the way such changes unfolded over time and factors that played a role in it. The second cluster (i.e. supplementary cases) comprises cases of narrower scope and time span, such as the ones related to technology substitution, or innovation diffusion. Briefly, the first cluster is used to develop the main structure of the framework, while the second cluster is used for specifying the details within this structure.

While considering each transition case from the literature, we first studied the key aspects whose behaviours occupy central roles in the overall transition discussion; e.g. organic farming in an agricultural transition case, or environmental concerns of the public in a waste management transition case. These are more like the protagonists of the transition cases that had been reviewed for the framework development process. We introduced general concepts
that correspond to such aspects considering the nature of them, and especially their role with respect to the societal function, and the related socio-technical system. For example, organic farming is one of the alternative ways of fulfilling the societal function of concern; i.e. agricultural food production. The general concept of the option is introduced to represent such alternative ways of fulfilling societal functions. After this preliminary stage of analysis, the basic concepts of the option and the actor (and a set of actor roles) emerged as the main building blocks of the framework, as will be elaborated in the following chapters.

Following this, we focused on processes that are related to changes in these basic concepts and their interaction; e.g. what triggers change, how does change take place (e.g. gradual, discrete), or what determined the pace of change. In this stage, we aimed to identify a set of ‘atomic’ change processes (i.e. mechanisms) that, when combined, can constitute the complex structure that drives transitional changes, and yields complex dynamics. During this investigation process, we cluster change processes according to similarities in the way they operate on the options or the actors at a general level (e.g. a gradual change in an option that is driven by economical resources of the system actors). The emerging clusters pointed out some general mechanisms, which needed to be further specified and grounded (both theoretically and empirically). The transition cases cluster is also used during this specification stage, especially for investigating the interaction of the basic concepts in the context of a transition process. Also, the supplementary cases are used in this stage of the framework development. This latter set of cases allowed us to focus further on the isolated change processes related to the options’ properties, or the behaviours of the actors, and provided both empirical grounding and detailed information for further specification. Besides these case studies, we also benefited from more conceptual and theoretical literature on some the mechanisms on, for example, technological development, or actor choices.

As already mentioned, in the light of new observations from the case studies analyzed, these concepts and mechanisms are refined, and sometimes redefined on continuous basis during the framework development process.

The case studies from the literature that are considered in this process, which include both the transition cases and the supplementary cases, are given in Table II.1.
Table II.1. Case studies from the literature that are considered in the framework development

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Short Case Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Transition in American mobility: horse-drawn carriages to automobiles</td>
<td>(Geels 2005c)</td>
</tr>
<tr>
<td>T</td>
<td>Transition in water supply in the Netherlands</td>
<td>(Geels 2005a)</td>
</tr>
<tr>
<td>T</td>
<td>Biogas</td>
<td>(Geels and Raven 2006)</td>
</tr>
<tr>
<td>T</td>
<td>Transition in domestic waste disposal in the Netherlands</td>
<td>(Geels 2006c)</td>
</tr>
<tr>
<td>T</td>
<td>Factory production in America</td>
<td>(Geels 2006b)</td>
</tr>
<tr>
<td>T</td>
<td>Transition in the Dutch waste management</td>
<td>(Loorbach 2007; Raven 2007)</td>
</tr>
<tr>
<td>T</td>
<td>Transition from coal to natural gas in the Dutch energy supply system</td>
<td>(Correlje and Verbong 2004)</td>
</tr>
<tr>
<td>T</td>
<td>Transition in the Swiss agro-food system: from industrial to biological agriculture</td>
<td>(Belz 2004)</td>
</tr>
<tr>
<td>T</td>
<td>De-carbonizing the energy system in UK</td>
<td>(Shackley and Green 2007)</td>
</tr>
<tr>
<td>T</td>
<td>Sustainable mobility transition in UK</td>
<td>(Nykvist and Whitmarsh 2008; Whitmarsh and Nykvist 2008)</td>
</tr>
<tr>
<td>T</td>
<td>Culture-triggered transition in water management in Spain</td>
<td>(Tabara and Ilhan 2008)</td>
</tr>
<tr>
<td>S</td>
<td>Standard setting in video format: VHS vs. Beta</td>
<td>(Cusumano et al. 1992)</td>
</tr>
<tr>
<td>S</td>
<td>Technological transitions in air transportation in the U.S.</td>
<td>(Mozdzanowska and Hansman 2008)</td>
</tr>
<tr>
<td>S</td>
<td>Path dependence and lock-in to pest control strategies in the U.S. and Israel.</td>
<td>(Cowan and Gunby 1996)</td>
</tr>
<tr>
<td>S</td>
<td>Induced technological innovation towards the control of SO2 emissions in electricity generation in the U.S.</td>
<td>(Taylor et al. 2005)</td>
</tr>
<tr>
<td>S</td>
<td>De-chlorinization of the paper production industry: comparative analysis of Nordic countries and the U.S.</td>
<td>(Reinstaller 2008)</td>
</tr>
<tr>
<td>S</td>
<td>Technological development in the energy sector via government incentives in the U.S.</td>
<td>(Norberg-Bohm 2000)</td>
</tr>
<tr>
<td>S</td>
<td>Social implementation and expansion of biofuels: comparison of the processes in the Netherlands and Sweden</td>
<td>(Hillman, Suurs et al. 2008)</td>
</tr>
<tr>
<td>S</td>
<td>Entrenchment of cystic fibrosis (CF) screening in Denmark</td>
<td>(Koch and Stemerding 1994)</td>
</tr>
<tr>
<td>S</td>
<td>Lock-in to the QWERTY-layout in keyboards</td>
<td>(David 1985)</td>
</tr>
<tr>
<td>S</td>
<td>Social-shaping of the modern bicycle</td>
<td>(Bijker 1995)</td>
</tr>
<tr>
<td>S</td>
<td>Emergence and rise of Bakelite as a moulding material</td>
<td>(Bijker 1995)</td>
</tr>
<tr>
<td>S</td>
<td>Fluorescent lighting in the U.S.</td>
<td>(Bijker 1995)</td>
</tr>
</tbody>
</table>

Abbreviations: 'S' for supplementary cases, and 'T' for transition cases
4.1. Introduction

The problems that raise the need for a transition are related to certain societal needs, and stem from a sort of dissatisfaction or concern about the way these needs are fulfilled, in the broadest sense. Most frequently discussed transition problems are related to societal needs, which have been an indispensible part of modern lifestyle, such as energy (Correlje and Verbong 2004; Raven 2007; Shackley and Green 2007; Verbong and Geels 2007), mobility (Mozdzanowska and Hansman 2008; Struben 2006; Struben and Sterman 2008; Whitmarsh and Nykvist 2008), and food and agriculture (Belz 2004; Holtz 2008). These needs are fulfilled via systems that incorporate technological artefacts, physical infrastructures, formal and informal institutions; i.e. socio-technical systems. This need-centered characterization of socio-technical systems has been widely adopted in the transition field (Brown and Vergragt 2008; de Haan 2010; Elzen and Wieczorek 2005; Geels 2005b; Shackley and Green 2007; van den Bosch, Brezet et al. 2005). A similar perspective is also used in this study, and the societal need is located at the very core of the analysis: it is the major concept that sets the boundaries of the analysis, as well as of the socio-technical system of concern. In that respect, the societal need is the starting and also the anchoring point for analyzing a transitional change process according to the actor-option framework.

Three other aspects supplement the societal need in defining the scope of an analysis, hence, the boundaries of the conceptual representation to be developed according to the actor-option framework. Two of these aspects are the temporal (e.g. 10-year, 100-year) and the spatial (e.g. regional, national, global) scope of the analysis. The third aspect is a set of transition-characterizing issues. In a particular analysis, not all directions of change are of interest, and it is generally a major change with respect to a certain issue, or a set of issues that is of interest (e.g. fuel mix in mobility system, control structure in the electricity supply system). These three aspects with the societal function of concern identify the transitional change process in focus, and set the boundaries of the analysis.
A system-wide change, such as a transition, can be possible as a conjoint consequence of a set of smaller-scale changes in different parts of the system, as well as in the way these parts are interrelated. However complex these change processes are, their consequences relevant to a wider transitional change are about which alternative means or ways are being utilized for the fulfilment of the societal need; e.g. which alternatives are becoming obsolete, which alternatives are taking over the dominance of the way the socio-technical system functions. These alternatives constitute the first conceptual building block of the actor-option framework, and referred to as options. However, the options do not possess a dynamic nature themselves; both their nature and their role in the socio-technical system are shaped by the behaviours of the social actors of the system. Therefore, the actors are the second conceptual building block of the framework. Briefly, according to the actor-option framework, a transitional change is conceptualized as a conjoint consequence of the changes related to the options, actors, and the way actors and options interact. In the following two sub-sections, the building blocks of the framework are further elaborated. The third section focuses on the dynamic nature of the actors and the options, and discusses the interrelated nature of changes in these two main concepts.

4.2. Options

An option can be defined as an alternative choice that can be utilized for fulfilling a societal need. Depending on the need, an option can just be a physical artefact or a technology. However, in most of the cases, an option is more than that; it also incorporates the way that artefact/technology is used. For commuting needs, using private cars, car-pooling (e.g. Mitfahrzentrale in Germany (Mitfahrzentrale 2010)), or car-sharing (e.g. Greenwheels in the Netherlands (Greenwheels 2010)) are three alternative options. Although the artefact, i.e. the automobile, is identical, the ways this artefact is being used differentiate these three as distinct options. In the same context, for example, public transportation can also be considered as an alternative option, which relies on different technologies.

Despite being similar in function, the options may differ significantly with respect to various properties. This multi-dimensional variety, i.e. variety with respect to multiple properties, is one of the issues that are important in understanding and unravelling the complexity of transition dynamics. We consider two types of differences; differences with respect to transition-characterizing issues (e.g. emission performances of a mobility option), and differences with respect to the properties that system actors care about in their decisions (e.g. price).

As mentioned earlier, the options are more than isolated physical artefacts. Therefore, the properties that differentiate the options are not just related to the techno-physical aspects, but also go beyond that and are related to the contextual embedding of these options. Two broad classes of properties are identified. These classes are mainly based on the way these properties are related with the nature of the option, and with the way these properties change in the context of the actor-option interactions. These classes are discussed below;

a. Embodied properties

These are the properties mainly related to the techno-physical nature of the options, and as the name clearly indicates they are embodied in the option. In other words, these are properties that can be observed even when the option is studied in isolation from its socio-technical context. In the case of Beta-VHS video formats’ competition (Cusumano, Mylonadis et al.
1992), the technical properties of these standards like sound and picture quality are typical examples of the embodied properties. In general, such properties change either due to changes in the physical nature of the option (e.g. change in size, different material, etc.), or in the technology embedded in the option. In that respect, changes in the embodied properties are mainly dependent on innovations directly related to the option.

b. Disembodied properties
As the name implies, these properties are not related to the nature of the option itself as a standalone object, but related to the context in which the option functions. For example, consider public trains as an option for personal mobility needs. The important properties are not confined to the technical properties of these trains; other aspects such as the frequency and reliability of the service, or the crowding level are also important. These latter properties are mainly dependent on the contextual factors like the infrastructure and passengers’ overall tendency to use the public trains. When the factors that influence the dynamics of these properties are considered, it is beneficial to further categorize the disembodied properties as provisional (i.e. related to the way it is provided/supplied) and practical (i.e. related to the way it is used) properties:

i. Provisional properties
These are the properties related to the way options are provided to the potential users. The functioning of the option in fulfilling the societal need is dependent on a provision system (e.g. sales, distribution, service, maintenance, infrastructure, etc.), and mainly on the state of this provision system determines the provisional properties of the related option. Going back to the Beta-VHS example given above, the number of sales and rental points is a provisional property of the VHS option; this property is important in the context of competition against Beta since it determines ease of access, and it is independent of the VHS option’s techno-physical nature. Clearly, such provisional disembodied properties are directly influenced by the developments in the systems related to the provision of the option.

ii. Practical properties
Some of the disembodied properties are directly related to the utilization of an option. The number of households using the Beta standard is an important aspect, a property, considering that it differentiates the Beta from the VHS system over the course of dominance struggle between these two options. First of all, this property determines the possibilities of exchange, and access to variety. Secondly, it is a property that forms the basis for a hype perception on the potential users’ side. As can be seen from the example, such properties are directly related to the utilization pattern of the option among the system actors, and therefore, they change as a direct consequence of the utilization choices of these actors.

The changes in option properties, as well as in the role of an option in the socio-technical system (e.g. its dominance in the system) are important developments considering transitional change processes. However, options do not possess a dynamic nature by themselves, but all option-related developments are the consequences of related social actors’ behaviours, such as commuters shifting to a new mode of commuting, or manufacturers allocating resources for a new technology. Therefore, social actors and their behaviours are central in understanding the transition dynamics. The following section discusses the way these actors are conceptualized according to the actor-option framework in order to address their transition-relevant behaviours.
4.3. **Actors**

*Actors*, and in particular their decisions, are the main drivers of change in socio-technical systems. Although *options* are also an important aspect in the change processes, they are more like passive entities whose roles in the system's functioning are mainly shaped by the actions of the actors. Even in the case of a technological breakthrough, the transformation of a socio-technical system based on this breakthrough can only be realized via the actions of different actors in the system (e.g. infrastructure, regulation, policy making, users, investors).

Contrary to what the term implies, an *actor* in the *actor-option framework* does not necessarily correspond to an individual person in the socio-technical system, but it is a social unit of analysis, which can be attributed goals, preferences, resources, and actions. Based on this depiction a group of individuals, an organization, or a firm can also be considered as an *actor* in our conceptualization. In general, an *actor*, according to the *actor-option framework*, is an abstraction representing a set of social entities sharing similar goals, preferences and action capabilities.

As mentioned before in this text and elsewhere (e.g. Rotmans 2005), one of the key characteristics of transitional change processes is their multi-actor nature. These processes are multi-actor in the sense that they are driven by the interaction of a multiplicity of actors. However, there is more in this multi-actor nature than just multiple agents interacting (Geels, Elzen et al. 2004). These interacting actors are not identical, but they possess very different properties, such as their preferences, objectives and resources. In other words, transitional changes in socio-technical systems are driven by a set of actors, which are heterogeneous in multiple dimensions. However, the heterogeneity related to the causes and consequences of the actor decisions is of primary importance with regard to the way socio-technical system's functioning might change over time. Therefore, two broad dimensions of heterogeneity are especially important for analyzing transitional change; heterogeneity with respect to decision drivers, and heterogeneity with respect to decision consequences.

**a. Heterogeneity in decision drivers**

Before discussing the factors that yield heterogeneity with respect to the actors’ decisions, it is necessary to mention the way decision-making processes are conceptualized in the framework. At a general level, our conceptualization is based mainly on Simon's *bounded rationality* perspective (Simon 1955; Simon 1984). Although the actors are assumed to be intentionally rational (i.e. coherent and consistent), they are constrained by internal (e.g. cognitive capacity) and external (e.g. imperfect information) factors in decision-making.

First of all, an *actor*'s decisions are driven by what is known to the *actor*. Therefore, a clear source of heterogeneity is the *information possessed by the actors* in the system. The perfect information assumption in the complexity of the socio-technical systems is unrealistic, and possible differences among the *actors* in the information possessed about the *options* can lead to decision heterogeneity among the *actors*.

Secondly, the *actors* can diverge in the decisions they make due to the differences in the factors that determine the way this information is evaluated during the course of a decision making process.
Following the main frame of the *prospect theory* (Kahneman and Tversky 1979; Tversky and Kahneman 1992), a decision making process is conceptualized in two stages; *framing* and *valuation*. Actors subjectively frame alternative courses of action based on what they know about them, and make a decision as a consequence of valuing this framed information. Framing may relate to various aspects of a decision process (Tversky and Kahneman 1981), but we consider *framing of the decision outcomes* the most relevant one in our analysis context. Generally, outcomes of a certain action, or attributes of a certain alternative are judged against a neutral reference outcome (or simply a reference). Such a reference may be a state to which an actor has adapted, a set of social norms, or a level of aspiration (*ibid.*). Similar concepts are referred to as *aspiration levels, reference points, or target levels* in the decision-making literature (Einhorn and Hogarth 1981; Payne et al. 1992; Siegel 1957; Simon 1955). In our conceptualization, these references define what is acceptable/desirable for the actor. These standards, norms and habits of the actors’ can act as an important source of heterogeneity in actor decisions.

It is argued that the *actors* generally evaluate the direct consequences of alternative actions (i.e. ‘minimal accounts’ as Tversky and Kahneman (1981) name it) in decision-making process. However, in some cases an action can be related to an existing account linked to similar actions taken in the past (e.g. sunk-costs due to previous investment decisions). In such cases, the personal history of an *actor* also becomes influential in the decision process besides direct consequences of the considered actions. In that respect, the *commitments of an actor* (e.g. financial, or effort-wise) in the past can be as important as the options’ properties in influencing the decisions. Naturally, different levels of commitments to certain courses of action will differentiate the decisions of the actors even when they are exposed to identical information.

The assessment of the possibilities (e.g. *options*) before making a decision is not a simple uni-dimensional assessment; *actors* face a multi-dimensional assessment problem. In this context, it is the *preference structure* of the actor, which represents the relative importance of the different issues, such as environmental friendliness, loss of former investments or operating costs, for the actor. This can be seen as the mindset or character of the actor in the context of a given socio-technical system. Naturally, actors valuing issues differently will go along different courses of action, yielding to heterogeneity of actor decisions in the system.

Among these four factors that may lead to heterogeneity in actors’ decisions, the first one corresponds to the information possessed by the actor, while the other three are related to the way an actor evaluates this information. These last three factors, i.e. *references, commitments* and *preferences*, constitute the *actors’ behavioural identity*, which determines the behavioural tendencies of the actor in the context of transitional change.

**b. Heterogeneity in decision impact**

The nature of an actor’s decisions’ impact (i.e. which aspects of the socio-technical system, or the available options are influenced by the decisions of an actor) is primarily dependent on the *role* the actor occupies in the context of a socio-technical system. When we consider the fulfilment of a societal need as a sort of social interaction, we identify, by deduction, four main categories of actors involved in this process (Figure 4.1).
The first category of actor corresponds to the demand-side of the societal need: the actors of this category are the ones who have such a need, and use available artefacts and practice possible ways for fulfilling this need. These actors are categorized as the practitioners/users in a socio-technical system. Dominance of a certain option in the considered socio-technical system is defined in terms of the level of practitioner usage. For example, in the mobility case, commuters can be seen as the actors having the practitioner role.

Naturally, there is the other side of this social interaction, which is related to the provision of the means of fulfilling the societal need, which are used by the practitioners/users. Using the word in a broad sense, this side can also be seen as the supply-side of the societal need fulfilment process. These actors, who are labelled as the providers, are responsible for the provision systems that correspond to each option, and are mainly involved in making the alternative options available to the practitioners. This includes, for example, maintaining infrastructure, manufacturing a certain artefact, operating a service and providing maintenance services.

However, neither the utilization, nor the provision of the alternative options takes place in an unstructured manner. Both sides of the need fulfilment process are structured via a set of regulations and formal/informal rules. The actors who are related to altering such regulations and rules constitute the third category of actors; the regulators. As can be seen, the regulators are not directly involved in the need fulfilment process. However, they influence the way it is done via ‘changing the rules of the game’; e.g. imposing new rules, changing the regulations. For example, a government agent banning a certain practice, setting standards for certain environmental issues or providing subsidies is a typical example of an actor in this category. The aforementioned three actor categories almost complete the picture about the fulfilment of a societal need; briefly, the actors with the need, the actors who offer the solutions, and the actors who set the rules of interaction. There is another type of actor that is not directly involved in this process, but is important in shaping the way others behave in the need fulfilment context. These are the actors who can influence the way other actors behave with the opinions they hold about the need itself and the available options. For example, public support or opposition from NGOs regarding a certain option, like ICE-automobiles, may

![Figure 4.1. General actor roles](image-url)
influence the other actors’ actions in the system, like government bodies being more inclined towards imposing additional tax on high emission ICE-automobiles; or it may even induce more R&D budget allocated to alternative technologies by car manufacturers. As can be seen from these examples, the actors who can be labelled as opinion groups are sort of sideliners, but may have an influence on the other actors’ behaviours.

Besides an actor’s role, the possible extent of impact of the actor within the given context is another factor that differentiates the influence of the actors’ decisions on the way system functions. Among other things, the extent of the impact is mostly related to the resources controlled by the actor. Besides this, for different actors and for different contexts, the concept of power may correspond to different things. For example, consider the electricity supply context: the financial resources of a generation company can be considered as a measure of this actor’s power, since it determines the extent of the impact when this actor decides to invest in a certain generation option. The issue is a bit different for end-users in the same context. When an end-user decides to shift from a certain electricity supply options to another one, the impact of the actor will be proportional to the electricity consumption of the actor. The impact of a single household when it shifts to green-electricity would not be similar to the impact of a large-scale industrial user making the identical decision. Therefore, the possible extent of impact concept constitutes an important aspect of the way actors are conceptualized according to the actor-option framework.

4.4. Interaction of the actors and options

Two key concepts, i.e. actor and option, are discussed in the previous sections. These concepts can be seen as the building blocks for the two very closely related parts of the socio-technical systems; the actor for the social, and the option for the techno-physical parts. Along a transitional change process, neither the actors, nor the options stay as they are, and they both change over time. Moreover, the dynamics of the actors and the options are not independent from each other; i.e. a change in the behaviour of the actors trigger a change related to the options, and vice versa. The relevance of the co-dynamics of these two parts in explaining significant changes in the socio-technical systems has been already discussed by various authors (e.g. Bijker 1990; Geels 2005b; Hughes 1987; Shove 2003). In the context of transitions, decoupling these two interrelated sides, and trying to understand their dynamics in isolation from the other can easily lead to missing an important part of the explanation behind a transitional change process.

The following subsections provide a general discussion on the ways the actors and the options change over time. First of all, both the behaviour of the actors, and the nature of the options may change due to developments beyond the boundaries of the socio-technical system. Technological breakthroughs, or global economic crisis are some examples of such developments. Secondly, the actors and options can change in an interrelated manner within the structure of the socio-technical system. This latter type of change processes, i.e. endogenous changes, is very important in understanding the internal dynamics of the socio-technical systems. Therefore, the discussion will primarily focus on the interrelated changes of the actors and options.

The discussion on the actor-option dynamics can possibly be structured using different frames of reference. In the actor-option framework, the actor behaviour serves as the key concept in
structuring such a discussion. In that respect, following sections discuss changes triggered by the actors’ behaviours, and changes in the factors that influence these behaviours. Before proceeding into these discussions, it is worthwhile to clarify the nature of these behaviours that are relevant in a transitional change context.

The behaviour of the actors in relation to the options are the main motor of change in socio-technical systems, as discussed also by Geels (2005b). The type of actor behaviours shows great variation considering the scale of socio-technical systems, and multiple actors heterogeneous in, for example, goals and roles within such systems. However, at a more general level the nature of transition-relevant behaviour of all these system actors show significant resemblance: whatever the actual behaviour is, it is driven by a choice related to the options; the actors choose which option to support, oppose, use, or invest in. For example, consider a mobility case; for a practitioner, the decision is to choose among the available transportation options to use. On the other side, a provider would be choosing in which transportation mode to invest. Finally, for the government being a regulator in the system, the choice is whether to support a mobility option, and if yes, which one.

a. Changes triggered by the actor choices
The actor choices are introduced as the main motor of change, and the realization of such a change takes place via the impact of the actor choices on the options, on other actors and also on the way system functions. However, the extent of change can be very different: the change may span from short-term changes in the way system functions within its existing structure (i.e. change in the surface) to long-term changes in the structure of the system (i.e. change in the depths). It is fruitful to, at least, distinguish the two extreme points of this scale in discussing change induced by actor choices;

i. Change in the surface...
The short-term changes are more at the operational level, and are about the way the system functions within its already existing structure. In other words, such dynamics are not directly related to deeper changes in the structure of the system that characterize transitions. In some cases, the practitioners may have access to multiple options for fulfilling the societal need of concern. For a commuter, it is possible to use public transport, a personal automotive, or even a bicycle to commute in a given day. The choice of the practitioner among these options has an immediate impact on the way socio-technical system functions, and consequently on the system performance. For example, it influences the traffic density, the crowding in public transport, or daily carbon emissions from the whole mobility system. Apart from influencing the overall functioning of the system, the practitioners’ choices may have an immediate effect also on practical properties of the options. The crowding example mentioned above is such a change of the properties of the public transportation option as a result of practitioners’ choices.

A similar pattern holds for the provider decisions: the providers may have access to multiple means of directly providing or indirectly supporting the provision of a certain option. In such cases, the choice of providers among these accessible means influence the operational performance of the socio-technical system. A good example is electricity generation. Electricity supplied via the central grid is an important, and also the dominant option used for electricity needs. Assuming no change in the behaviour of the practitioners regarding their
energy consumption (i.e. identical electricity demand), the providers may generate electricity using different combinations of generation facilities in the generator park of the electricity system. Such operational choices of the providers have immediate consequences regarding, for example, overall carbon emissions or average generation costs. While the change in the overall carbon emissions is related to the functioning of the system, average generation costs, which is the basis for electricity prices, is a provisional property of the grid-based electricity supply option. As in the case of the practitioners, the short-term impact may be both on the overall system functioning, and an individual option’s properties.

In both the practitioners’ and providers’ cases mentioned above, the consequences of the actors’ choices are short-term changes, and they are changes on the surface. However important such consequences, they are not structural; the system structure stays intact, but the way this structure functions is altered. As a result of this, such changes are easily reversible. Although such consequences are not transitional change in the sense considered in this dissertation, they may trigger further long-term change processes that lead to transitions.

### ii. Change in the depths...

The consequences of actor choices are not confined to the (short-term) operational changes mentioned above. These choices also yield long-term changes that alter the structure of the socio-technical system. Simply put, the changes mentioned in the previous paragraphs are more about the way the options are used; however, the deeper impacts of the actors’ decisions may alter the set of available options, as well as these options’ properties. The actor roles discussed before are based on the type of impact these actors have on the system, as well as on the individual options. Therefore, it is convenient to discuss examples of structural impact of the actors with respect to the roles they play in the socio-technical systems.

At the first glance, the impact of the practitioners may seem to be just at the operational level, which is discussed above. However, their impact goes much further, especially via influencing the social aspects related to the options. First of all, the aggregate behaviour of the practitioners at a given point in time may influence the future behaviour of the other actors: a wider acceptance of a certain option may make other actors more likely to make similar choices, as it is the case in hypes and bandwagon behaviours. Practitioners’ choices over time also play an important role in the creation and modification of social expectations, norms, and standards. These aspects are not directly related to particular options, and therefore, it is difficult to talk about a direct impact on the options by this means. However, changes in such social aspects influence the options’ evolution over time via altering the way these options are perceived and assessed by the actors. In other words, the practitioners’ behaviours go beyond short-term changes, and can also influence the social embedding of the options, which influences the evolution of the system over time.

Providers play a major role in a socio-technical system’s development, and especially in the developments related to the techno-physical aspects of the system. Such developments may be realized in the embedded properties of the options (e.g. fuel efficiency of automobiles), which are fuelled with intellectual and economical commitment of the providers to the options. An option that is favourable to the providers is more likely to develop in the directions relevant for its empowerment in the socio-technical system, compared to an option that fails to attract provider resources. Moreover, the providers’ behaviour directly influences the provisional
properties of the options, since the development and maintenance of the provision system are mainly dependent on the providers’ actions. For example, in the case of the historical water supply transition analyzed by Geels (2005a), the accessibility of piped water –one of the options- is a typical provisional property, and the change in the accessibility is dependent on the investments of the water suppliers on the pipe networks.

Unlike the previous two actor groups, the regulators influence the change processes indirectly. Such an indirect influence is made via intervening in the choices of the practitioners and/or providers in the system. Firstly, this is possible via setting standards for certain option properties (e.g. emission standards for waste incineration), which can be seen as sort of pre-selection of the options to be used by the practitioners. Additionally, the regulators may directly alter the option properties using, for example, taxes and subsidies (e.g. congestion tax). In both forms, the choices of the regulators have an impact on the way system unfolds over time by conditioning the future behaviour of the other actors within the system.

The impact of the opinion groups on the functioning of the system is also indirect. Their choices with regard to the options can create a social support or opposition with regard to an option, via which the opinion groups can influence the future behaviour of other actors. For example, the public opposition to nuclear energy is one of the primary reasons behind the ‘no nuclear’ policy of the Dutch governments, i.e. a regulator of the energy supply system. Also in the Spanish water transition case discussed by Tabara and Ilhan (Tabara and Ilhan 2008), NGOs like CODA, Greenpeace and COAGRET play an influential role in influencing other actors in the system. As can be understood from the depiction, in order for opinion groups to have an impact on the system, the existence of other actors who take the opinion groups’ positions into consideration is essential. In other cases, these groups’ impact on the way the system behaves over time will be absent, or minimal at most.

b. Changes in the actor choices
The factors that cause short- and long-term changes in the way the actors behave in a transition context can be considered in two separate groups. The first group is related to the actors’ environment (including the options), and what an actor knows about this environment. The second group is related to the changes in the behavioural identity of the actor in the decision context; i.e. factors related to how an actor evaluates the environment. We discuss these two groups in the following paragraphs.

i. Choices shaped by what is known
A very important aspect of the environment is the set of options that are available to the actors. As actor decisions shape the way options change over time, these decisions are also shaped by the information known to the actor about the options. The information about the embodied and disembodied properties of the options constitutes the basis of the actor decisions in the context of transitional change processes. Therefore, the choices may change as what is known to the actor changes. This intuitive dependency of choices on actors’ knowledge about the options, coupled with the dynamic nature of this information can play an important role in the way a transitional change unfolds. The dynamic nature of actors’ knowledge is a result of two phenomena: the imperfect state of that knowledge, and the dynamic nature of reality.

The actors make their choices based on limited and imperfect information about their environment. Information about the options can be discussed in two levels. At the higher
level, it is about being aware of an option as a viable one; in other words, about the inclusion of the option into the choice set of the actor. The second level is at the detail level of the option properties; information about comfort level, operating costs, or number of fuelling stations of an option. The information of an actor may be imperfect at both of these levels. The actors observe and collect information about the options, and update their knowledge about these options based on this new arriving information. Such a knowledge-updating process is one of the issues that make the actors’ knowledge dynamic, even when nothing is actually changing in reality; i.e. option set is fixed, and options’ properties are static.

However, the socio-technical systems, and specifically the options therein, are far away from being static. The properties of the options change, and new options, i.e. innovations, appear within the system over the course of a transitional change process. Therefore, while actors are collecting information about their environment, the environment is also changing. First of all, these changes in the environment contribute to the imperfect state of information possessed by the actors. Secondly, such changes, especially related to the options, may also trigger changes in the way actors behave. This completes a high-level feedback between the actors’ behaviours and the options; i.e. actor behaviour may yield changes in the option, as already discussed in the previous section, and changes in the options may trigger changes in the way actors behave.

The actors update their information on the options, or on the system in general, via ‘learning’ processes that can be generalized as processes of information flow. The actors may learn through their own experiences, through social interaction with other actors, or from external sources (e.g. global marketing campaigns).

ii. Choices shaped by actor’s behavioural identity...

Since the actors’ choices are taken as the key issue, the ‘behavioural identity’ of an actor is a combination of factors that differentiate the actor from others under similar conditions in the decision making process. Such an identity, which supposed to be an important determinant of an actor’s choices, has a dynamic nature, and evolves over time as a consequence of interaction with the options and other actors.

Personal histories matter...

One of the factors that differentiate actors’ choices is the information possessed by the actors, which is discussed in the previous section. However, actors’ decisions are not just dependent on recent information about the options, or the system; but ‘personal’ history of an actor with the options also plays an important role. This personal history may involve years of experience with an option, large amount of capital investment made on the infrastructure, and significant amount of engineering know-how accumulated, for example. The actors are not identical with respect to this type of tangible and intangible assets accumulated over years. Such assets can generate a commitment to an option, and cause an actor to continue a certain course of action due to the actor’s personal history. Firstly, the commitments can differentiate the actors in their choices. Secondly, the committed actors can generate a sort of inertia against change in the socio-technical systems (Cowan and Gunby 1996), or, in other words, create a ‘momentum’ along the historical trajectory of the socio-technical system (Hughes 1983).

If the information about the nature of the options and the overall state of the socio-technical system can be characterized as the objective basis of actor choices, the personal history
of the actors constitute the subjective basis. This subjective basis changes over the course of a transitional change as a result of the actors’ decisions with regard to the options (e.g. investments in an option in the past may increase the actor’s commitment to investing in that option), and is one of the factors that make actors’ identities dynamic, which can contribute to the dynamic complexity of transitional change processes.

Assessments as a matter of reference...
Another important aspect of an actor’s identity is the set of standards, expectations, and norms: How much is cheap? How much noise is acceptable? How fast is considered as fast? The answers to this type of questions constitute a set of references for the actors to be used in assessment of the options. For example, minimal comfort an actor expects from a mobility option will serve as the basis for evaluating available options. Such references are subjective and differ among the actors as in the case of personal histories. Apart from that they are not static, as well. Firstly, such references evolve over time as a consequence of interaction with the options; i.e. options shaping the expectations of the actors. An actor’s favourite option can set the actors expectations and minimal standards, and this causes the actor to evaluate a new option based on the merits of the previously utilized one. Secondly, these references of assessment can also change via social influence. Other actors in the network of an actor constitute examples of what is normal, what is socially acceptable, and/or what are the minimal standards the actor can expect. Since such references are of key importance in the assessment of novelties by the actors, the way they develop is important in the unfolding of a transitional change.

Preferences indicating what is important...
The final aspect of an actor’s behavioural identity, in the specific context depicted in this text, is about the relative importance of different issues for the actor; i.e. the actor’s preference structure. Considering the typical time span of transitions in large-scale socio-technical systems (i.e. multiple decades), it would be misleading to assume that the preference structures of the system actors stay intact. New issues may become relevant for the actors’ decisions, and the relative importance of the issues may change. For example, it can be claimed that environmental impact was not an issue in mobility choices, or whether food production was organic or industrial did not matter that much two decades ago in the western societies. The dynamic nature of the preference structures relates to changing values in the social part of the socio-technical systems.

According to the *actor-option framework*, changes in the preference structure can take place due to developments that are internal or external to the socio-technical system. The internal developments are the ones related to the internal functioning of the system, and are the result of the endogenous dynamics of the system. The actors, being reflective and adaptive social entities, observe and assess the developments within the system, as well as the overall outcomes of the system functioning. An increasing discontent with such observations may lead to a re-arrangement of the priorities for the actor. Apparently, the factors that influence the preference structures of the actors are not confined to the boundaries of a socio-technical system. Social, economical, or ecological developments exogenous to the system of concern may also have very strong impact on what is perceived as more important. Such exogenous changes correspond to the so-called ‘landscape dynamics’ in the terminology of the multi-level framework of transitions. These external developments can be in the form of external shocks (e.g. crisis, accidents), or in the form of long-lasting slow changes (e.g. cultural change).
4.5. Conclusions

In summary, this chapter introduced the basic concepts of the *actor-option framework*, and also sketched a general overview of their interactions that depict the change processes within a socio-technical system in the context of a transitional change.

In the short run, the overall performance of the system is dependent on the actor choices, and the corresponding options’ properties (e.g. total carbon emissions from an electricity supply system is dependent on utilized generation means and the emission performance of these means). Long-term changes related to the options (e.g. technological properties) and the provision systems (e.g. infrastructure) supporting them are driven by the actors’ behaviours, or exogenous developments. On the actors’ side the situation is more complicated. In the short-run their behaviour may change due to changes in what they know. Apart from that, actors’ behavioural identities, which are the main driver of their choices, are altered due to other actors’ choices, the way system functions, changes in the available options, or due to exogenous developments (Figure 4.2).

Consequently, the overall sketch provided in this section is a general frame to structure the analysis of internal change processes in a socio-technical system, but does not tell much about the nature of these change processes: despite emphasizing the role of the actors’ choices on the changes of the options, for example, little has been said about what kind of actors trigger what kind of changes. This constitutes the topic of the following chapter.

![Diagram of actor-option framework](image-url)

**Figure 4.2. General interaction scheme of actors and options**
5.1. Introduction

According to the actor-option framework’s general scheme, which is introduced in Chapter 4, internal change processes of a socio-technical system that lead to transitions are explained in terms of actors, options, and their mutual interactions. However, such a depiction is very general and abstract depiction of the internal change processes within a socio-technical system.

In this chapter, we address this issue by going deeper in detail with regard to the change processes in the actor-option framework, and we introduce a set of mechanisms to complement the actor-option framework’s general scheme. Briefly, these mechanisms are specific instances (i.e. different manifestations) of the change processes and interactions of the general scheme; e.g. different processes through which an actor may change an option’s properties. The set of mechanisms to be introduced comprises processes that are commonly encountered in different socio-technical systems. These mechanisms are simple themselves, and they constitute the atomic pieces that can be used to reconstruct the complex internal web of interactions that drive the socio-technical systems’ behaviours.

In the following section, we elaborate on the concept of mechanism in the context of this dissertation, and briefly discuss the mechanism identification process. Following that, the chapter introduces the basic mechanisms related to the ways options’ properties, actors’ perceptions, and actors’ behavioural identities may change. Before concluding the chapter, we demonstrate how simple mechanisms can link up to create complex feedbacks in a socio-technical system, using two simple illustrative examples.

5.2. Identifying mechanisms of change

While discussing the motivation behind the development of the actor-option framework in the introduction to Part II, one of the issues discussed was about identifying a set of common processes that play a major role in conditioning several transitions. The overall picture laid
down in the previous chapter guides the search for such common processes, i.e. *mechanisms*, in transitional changes in socio-technical systems. For this purpose, a set of case studies from the literature\(^1\) as well as some theoretical literature on innovations and technological change, have been reviewed in order to inductively construct a portfolio of *mechanisms* that are particular instances of the major change processes discussed in the previous chapter.

During this induction process, a *mechanism* is characterized as a chain of events and processes that constitute a regular link between a trigger event or condition, and a consequence. In other words, the *consequence* is more likely to be observed when the trigger event happens, or the trigger conditions exist, *ceteris paribus*. Such a depiction is quite similar to the social mechanism characterization of Hedström and Swedberg (1998b). This is still a broad categorization and various regularities with various complicatedness levels can be labelled as a *mechanism*. Other criteria used in the identification of the *mechanisms* are as follows:

- **Generality:** A *mechanism* should not be just specific to a particular context or case, but should be identifiable in a group of transitional change processes.
- **Simplicity:** Individual mechanisms are simple to be used as an atomic unit in an analysis. If an observed regularity spans multiple major changes mentioned in the previous section (e.g. a regularity involving actor choices changing system performance, and this change influencing other actors), multiple mechanisms are sought in that regularity.
- **Policy-relevance:** While aiming for generality over multiple transitional change cases, the abstraction level of the *mechanisms* are constrained with the requirement of residing at the policy-relevant level, i.e. it should be possible to link the events and processes that constitute the mechanism to their policy-relevant real life counterparts.
- **Empirically and/or theoretically grounded:** A mechanism is either supported by empirical data from multiple cases and/or by theoretical literature, or intuitive enough to postulate its existence.

As a consequence of our review of the empirical cases mentioned in the introduction of Part II, and relevant theoretical work, a set of *mechanisms* common to transitional change processes in socio-technical systems is identified. These processes are not ‘common’ in the sense that they are observed in all transition cases. However, in most of the transition cases, it is possible to recognize a subset of this *mechanism* set active, and the *mechanisms* in this subset and their co-dynamics provide an explanation for the observed transition dynamics.

The organization of this chapter follows the structure of the discussion on the dynamic and interrelated nature of the *actors* and the *options* given in the previous chapter. The first group of *mechanisms* is related to the dynamics of the *options*, and mainly to the changes induced by the *actors’* behaviours. Following that, the mechanisms related to the information possessed by the *actors* are introduced. This group is the first of two that is related to the changes in the *actor* behaviour, and the *mechanisms* in this group mainly relate to changes in the shorter term. The last groups of *mechanisms* is about deeper changes in the *actors* with regard to the way they make their decisions; mechanisms that alter the behavioural identity of the *actors*.

### 5.3. Mechanisms related to option properties

An option is defined as a distinct alternative for fulfilling a societal need, and it is more than *just an isolated technological artefact*. A characterization based just on the artefact aspect of\(^1\) See the introduction to Part II for a discussion on the list of case studies considered.
an option is not sufficient, and this characterization should cover the aspects of the option with respect to the provision system supporting the option’s functioning, or the actors’ utilization patterns that influence the social embedding of it. Those aspects are called the option properties, and these properties cannot be treated as static in a typical time horizon used in analyzing a transitional change process; i.e. multiple decades.

An option is said to change when the properties of the option change. These properties can change due to developments internal or external to the socio-technical system. This section introduces a set of mechanisms that link such developments to the changes in the option properties. The set includes four mechanisms, which are related to the developments internal to the socio-technical system altering the option properties, and to the external developments having consequences related to the options within a given socio-technical system.

i. **Experience-driven change in option properties:**

Experience-driven change is a general depiction for a set of option development processes. As the name implies, cumulative experience of the actors with an option leads to the option’s development according to this mechanism. Such a development can be caused by both provisional and practical experience.

When it is the experience of the providers that drives the development, this mechanism is equivalent to a widely known phenomenon; *learning-by-doing* (Argote 1999; Argote and Epple 1990; Arrow 1962; Muth 1986; Rosenberg 1982; Zangwill and Kantor 1998). According to this, increasing experience of the provider creates knowledge, which leads to the improvement of the option itself (i.e. techno-physical properties), or of the way the option is provided (i.e. provisional properties). For example, improvements in the locations of the bike stations, as well as the number of bikes in these stations, in a public bicycle rental system (e.g. bicing in Barcelona, velib in Paris) can be attributed to this mechanism. In the case of a manufactured artefact as an option, manufacturing costs, which influence the price of the artefact, gradually decreases over time as a consequence of the cumulative production; i.e. another example of experience-driven development.

In the case of the practitioners, it is the cumulative utilization of the option that yields to the option development. Rosenberg discusses this process using the term ‘learning-by using’ (Rosenberg 1982). Rosenberg, who discusses the mechanism in the narrower context of manufactured artefacts, distinguishes two types of development; embodied and disembodied. In the embodied case, the experiences of the users (i.e. practitioners) provide feedback for the manufacturers (i.e. providers), and this in turn leads to the improvement of the artefact itself. In the disembodied case, the users figure out better ways of using the artefact as a result of their experience with the artefact. In the former case, the generated know-how is embodied in the artefact, and in the latter case it is embodied in the users practices, not in the artefact. This distinction is still relevant for the option concept of the actor-option framework, which is broader than standalone artefacts. The embodied developments are related to the techno-physical properties of the options, whereas the disembodied developments correspond to developments in the practical properties. For example, fuel consumption of an automobile is highly dependent on the driving style, and the experience of the driver can lead to lower commuting costs with the identical automobile. Average yield with an insecticide-based

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2 Some other labels, such as ‘experience curves’ or ‘learning curves’, have been used for the same concept as well.
farming practice also can improve over time as the farmers learn more effective ways of applying the chemicals.

In the cases of both the practitioners and the providers, it is the knowledge gained as a consequence of the accumulated historical (practical or provisional) experience that yields the property development. Just as the knowledge, once obtained, such a development is preserved, at least in the short run, even when there is no further utilization or provision of the option. In cases where the changing property is a techno-physical one, the change is embedded in the ‘design’, and more likely to be preserved. On the other hand, the changes in the practical or provisional properties reside in the actors (i.e. individuals or organizations). In these cases, the property can also deteriorate over time unless the experience with the option is sustained. This ‘knowledge decay’ process has been discussed by Argote in the context of learning curves in the manufacturing systems (Argote 1999; Argote et al. 1990; Argote and Epple 1990).

**ii. Scale-driven change in option properties**

The scale of utilization (e.g. number of users), or provision (e.g. volume of production) of an option can have an impact on the option attributes in some cases. This general mechanism has both provider- and practitioner-driven manifestations, and the change induced by the scale may be negative, as well as positive.

Provision side instances of the scale-driven change are direct consequences of the provision scale, and are simply about more/less efficient exploitation of the provision opportunities. A straightforward example is the commonly experienced decrease in the unit costs in standard manufacturing or service systems as output increases. However, the impact need not always be positive in the scale-driven change. Especially, in the provision systems that consist of multiple sub-systems with heterogeneous capabilities, as the provision scale increases less efficient sub-systems need to be exploited. This in turn leads to an overall performance decrease in the provision system. Electricity supply is a good example for this; available generators are dispatched according to their generation efficiency, and as the overall output of the supply system increases less efficient generators need to be dispatched, causing the average electricity price to increase.

Practice side instances of the scale-driven change are related to the utilization scale of an option by the practitioners. The utility obtained from an option is not dependent just on its techno-physical properties, but other practitioners’ utilization behaviour can also be an important determinant of the utility. For example, the effectiveness of insecticide-based agriculture is dependent on the adoption scale of the practice in a geographical region. Since insects can travel across fields, the best performance of the practice in terms of insect extermination effectiveness can be achieved if all the farmers in a region adopt insecticides (Cowan and Gunby 1996). Additionally, network externalities observed in telecommunication systems (e.g. telephone), or online social communities are also typical scale-driven utility increases; i.e. the more users on the system the more benefit a user can get from the option. An impact in the opposite direction is also possible as a result of increasing utilization scale; i.e. crowding process. The crowding corresponds to deterioration of the properties of an option as a consequence of increasing load on the system (i.e. utilization scale of a particular option). For example, the availability of bicycles is important for potential users considering the public bicycle option for daily commuting. Keeping the number of bicycles in the system (i.e. system
capacity) constant, if the number of users grows unexpectedly, the availability of the bicycles, which is a provisional property, will drop significantly due to crowding.

This mechanism, especially when the impact is positive, may resemble the experience-driven change mechanism discussed in the previous section. Argote and Epple also raise their concerns about the possibility of confusing the learning-by-doing and the scale effect, two examples of the discussed mechanisms (Argote and Epple 1990). Simply, these two mechanisms both indicate that as, for example, the utilization level gets higher, some of the option properties get better. The difference becomes apparent when utilization levels decline. Even if the utilization level drops to null, the historically accumulated knowledge gathered via experience would be intact. Since it is this knowledge that is the source of experience-driven change, the property changes achieved via this mechanism would be intact, also. In other words, the knowledge acts like a buffer in between instantaneous utilization levels and the option properties, and decouples their dynamics. However, the situation is different in the case of scale-driven change: the changing properties are directly related to the instantaneous utilization level. The history is irrelevant, and once the utilization level changes, this change is directly reflected on the option properties in scale-driven changes. In simpler terms, once the utilization level, or the load on the system, disappears, the option property goes back to its former level.

### iii. Resource-driven change in option properties

The system actors also influence the properties of the options by utilizing the resources they possess. These resources are not only financial, but they also include, for example, physical capital, manpower, and time (R&D, managerial, etc.). In general, resource-driven changes are induced by purposeful resource allocations of the actors who aim to alter the option properties. In line with such an aim, these resources may be directed to three different aspects related to the option; the option itself, the means/methods of provision, and the capacity of the provision system.

The resources directed to the option itself mainly contribute to the development of the techno-physical properties. A typical example would be R&D resources spent on improving an artefact. These resources may be coming from the providers, but also from the regulator actors. The research funds provided by the U.S. government agencies in the electricity production field is a typical example of the latter (Norberg-Bohm 2000; Taylor, Rubin et al. 2005).

The means/methods of provision determine the provisional properties of the options. An option having the same techno-physical properties may be provided cheaper, for example, by improving the method of provision. In the case of the options with a pure service or practice nature, the role of the provision on the overall properties is significant. The actor resources may be used for improving these provision means/methods in order to improve an option indirectly against its alternatives. For example, incineration is one of the important waste management options. This option in the Dutch waste management system got better over the years in its environmental performance as a consequence of the improvements in the incineration process and equipment (i.e. the way waste incineration is provided), which was made possible by R&D resources spent on the issue (Loorbach 2007; Raven 2007).

The capacity of a provision system is dependent on, for example, the physical infrastructure
that enables an option to function properly, and is an important determinant of especially provisional properties of the related option. When left alone, this capacity can decay (e.g. due to aging), or the capacity may become insufficient in the face of growing demand for the corresponding option. Actor resources are the fundamental input for capacity expansion, or at least its maintenance. In short, while resources allocated to capacity development can improve some provisional properties, lack of resources can result in deterioration of these properties. In the historical transition from sail- to steam-ships (Geels 2002a), the range of steam-ships is dependent on fuelling stations on the route, and the availability of the option depends on the number of operational steam-ships: both properties develop as a consequence of capital investments of providers, i.e. shipping companies. In the case of water supply transition in the Netherlands (Geels 2006c), when the city government of Maastricht cuts resources for maintaining public pumps, the availability/accessibility of the groundwater option deteriorates over time.

iv. Exogenous change in option properties

The property changing mechanisms discussed so far are all endogenous to the socio-technical system being analyzed; the changes are triggered by the actions of the actors in the system. However, assuming that all option changes are endogenously driven would be hard to justify. The changes in the option properties may be rooted in the developments that take place beyond the boundaries of the socio-technical system being analyzed; i.e. developments that are autonomous from the dynamics of the system. For example, consider the Dutch mobility system. Electric cars are among the potential future options for this system. Some developments regarding the properties of these options, e.g. driving range, battery life, are driven by the factors, such as R&D policies and spending of global car manufacturers, exogenous to the Dutch system. These factors are labelled as exogenous because they are autonomous from the developments in the Dutch system. For example, global R&D efforts on electric cars would not change due to the demand in the Dutch market.

This type of changes can be also labelled as spillovers in the sense that they are due to developments in other systems. The spillovers can be observed in both embodied and disembodied properties of the options. Referring back to the example given above, an improvement in the driving range of electric cars achieved in R&D labs in Detroit would determine the range of electric cars to be released in the Dutch market. The spillover is related to the techno-physical nature of the options. Alternatively, the spillovers can be in the form of expertise or knowledge, which changes the disembodied properties of the option. For example, organizational know-how spillovers from other countries on efficient dispatching of city public bikes would improve the provisional properties of this mobility option. This latter form of spillovers resembles the widely discussed organizational spillovers (Ghemewat and Spence 1985; Ingram and Baum 1997; Ingram and Simons 2002).

Such spillovers can be considered in two classes: intra-domain and inter-domain spillovers. A spillover can be from another socio-technical system in the same domain (e.g. mobility), where the option serves the identical purpose; e.g. spillovers from American mobility system to the Dutch mobility system. Also a spillover can come from a different domain (e.g. from space research to mobility), where the option or option’s components are used; for example a technological improvement in the battery life achieved by NASA for space satellites can cause some spillovers to the electricity-based mobility options.
5.4. Mechanisms related to actors’ perceptions

As discussed before, it is mainly what is perceived by an actor that conditions its behaviour rather than complete and perfect information about the options, other actors, and the system state in general. Therefore, the processes via which actors’ perceived information change over time play an important role in the actors’ behaviour change. Apart from shaping the actors’ behaviours, the information dynamics within the system also have the potential of creating internal delays in the socio-technical system, and introducing significant lags between the developments (e.g. soil pollution, technological breakthrough, etc.) and the reactions to these developments.

The concept of ‘perception’ triggers an association with the subjectivity of the actors. Apart from being about ‘raw’ information about something, a perception may also incorporate the subjective meaning attributed to that information. In the way the term ‘perception’ is used in this book, it refers to ‘perceived information’; i.e. information known to an actor. The mechanisms discussed below are primarily about ‘learning about something’ and/or ‘gathering new information’. In that respect, they correspond to simple information gathering, and single-loop (or first-order) learning discussed in the organizational learning literature (Argyris and Schön 1978; Bateson 1972). It is the information that changes via these learning processes, not the values or norms used by the actors to attribute meaning to this information. The latter aspect, which can be considered as subjective evaluation of the gathered information, is closely related to the actor’s behavioural identity, and the mechanisms related to this identity will be discussed later in this chapter.

i. Individual learning

As mentioned earlier, information possessed by the actors about the state of the system, or the available options need not be precise. The individual learning mechanism refers to the improvement of the information precision via direct observation, or experience of an individual. In the simplest form of individual learning, the actors can learn via direct observation; i.e. observation-based individual learning. First of all, the actors can learn about the situation of the system; for example, the extent of environmental degradation or local pollution around the actors. Secondly, they can learn about the existence of a novel option. Thirdly, they can learn about the observable properties of the options. For example, an actor can learn about the physical appearance of an option, which might be relevant in the actor decisions. Similarly, an actor can learn about the availability of bicycle pickup points just by observation, even if the actor is not using the public bicycle rental option for commuting.

However, not all option properties can be learned just by observation; direct experience with an option is required for some of the properties. Kalish (1985) refers to this type of properties as ‘experience attributes’. In the experience-based individual learning, a provider’s, or a practitioner’s direct experience with an option (e.g. a practitioner using an alternative fuel vehicle, a provider investing in new generation wind turbine) enables the actor to learn about the actual properties of the option. For example, a hybrid car user can be expected to develop a better idea over the years of experience about the periodic maintenance costs of the car, which might be different from what is known to the user at the time of purchase. As seen here, such learning can be quite slow if a significant amount of accumulated experience is required for more precise information.
ii. **Social learning**

This learning mechanism is about the diffusion of information among the actors; it is the information possessed by other actors that acts as the source of new information for an actor. Information flow via social interaction (e.g. *word-of-mouth*, or *information contagion*) has been discussed as a very important process related to the diffusion of innovations (Geroski 2000; Hazhir and Sterman 2007; Rogers 1983; Young 2007). An actor, or a group of actors, using a novel option (i.e. user-actor) can gather new information via the *individual learning* mechanism. This newly gathered information is accessible to and can be learned by other actors who are interrelated with this user-actor. In summary, this is the mechanism via which actors learn about other actors’ experiences and information perceived by them.

This type of learning can have complex dynamics mainly due to the changes in the set of actors functioning as the information source. First of all, the actors in the source group are heterogeneous in what they know about a certain option, and these actors go through their own *individual learning* processes. Secondly, new actors can join this set during the learning process (e.g. another neighbour purchasing a hybrid car), and possibly increase the information heterogeneity of the source group; what this new actor knows may be different from what is known by other actors in the set. In short, even if the option of concern is not changing in any way, information flowing via social learning mechanisms about this option can change just due to social processes. This aspect of social learning and its plausible dynamic impacts on the diffusion of a novelty is explored and reported elsewhere by the author in detail (Yücel and van Daalen 2009c).

iii. **Learning from external sources**

Although personal experience and social communication are important means of learning, they are not the only ones. The actors are also exposed to information from numerous other indirect sources; marketing campaigns, bulletins, newspapers, and scientific reports. These all serve as information sources, and are also very important in shaping what is known by the actors. The special importance of this mechanism comes from the fact that this is the mechanism via which novel information gets introduced into a particular socio-technical system. For example, the adverse long-term effects of DDT (short for dichlorodiphenyltrichloroethane), which was a very widely used pesticide before 1980s, were unknown among farmers as well as consumers before 1960s. This information is introduced to the actors of, for example, the U.S. agriculture system via scientific reports, and popular science publications such as *Silent Spring* (Carson 1962).

5.5. **Mechanisms related to actors’ behavioural identity**

Actor decisions are conditioned by the properties of the options, or environmental conditions. However, beyond these, such choices are determined as a consequence of the subjective assessment of each actor based on the actor’s preferences, beliefs, norms and priorities; i.e. an actor’s *behavioural identity*, as the term is used in this text. The mechanisms that are discussed below are related to changes in this identity. Even in the absence of any external change (e.g. new options emerging), such mechanisms can lead to significant shifts in the actor choices, since they correspond to changes in what an actor evaluates as more important, necessary or satisfactory, for example. The changes induced by this type of mechanisms correspond to the type of changes that can be categorized as *double-loop (or second-order) learning* (Argyris and
Mechanisms of Change

Schön 1978; Bateson 1972), since the changes are related to the way actors behave under given conditions. In other words, these mechanisms yield changes in what actors consider as good, proper, or satisfactory.

As already discussed in Chapter 4, the actors are conceptualized as intentionally rational (i.e. consistent and coherent), but internally (e.g. having limited cognitive capability) and externally (e.g. imperfect information) constrained decision makers. In the context of transitional processes, three aspects that shape the actors' decisions are explicitly considered in the conceptualization, and they form the behavioural identity of the actor in a decision making process. This identity comprises actor's references, commitments, and preferences. The mechanisms to be discussed below are related to how these aspects may change over time, and alter the course of actors' behaviours. However, we want to clarify that most of the mechanisms to be discussed are black-box processes in nature; they are observed regularities, but the underlying processes are still debated; i.e. what kind of psychological, cognitive or social processes are responsible for these mechanisms is not clear. For the level of analysis conducted in this study, the regularity of the phenomena suffices, and it can be used as an atomic unit of analysis in the context of transitions.

i. Reference formation and change

An important concept related to option assessment is a reference point used for the assessment; a reference point against which properties of an option are evaluated. For example, personal expectations, social norms, and regulatory standards all constitute such reference points for assessing if an option is usable for the actor, and where the option's properties stand compared to the actor's expectations and standards. The assessment references can be considered as a sort of 'demand requirements' of the actors with respect to their societal need. Such requirements, or references, can be assumed static in the short-term, but assuming that they stay constant over a long-term transition process may be misleading.

The actors' requirements are formed and updated over time as the actors interact with the options, and exposed to relevant external information; an issue frequently discussed in the context of technology-user interactions (Bijker 1990; Koch and Stemerding 1994; Schot and de la Bruheze 2003). The change, or adaptation, of actor references is an important process, which is also proposed as one of the major processes that lead to lock-in situations in socio-technical systems, when the dominant technology or practice shapes the expectations of the actors from the innovations-to-be (Unruh 2000).

Reference formation/change can take place due to various factors. A reference can be dictated to an actor from outside, as in the case of laws and regulations. Mostly, the dictated references serve to assess if an option is acceptable/allowed for the intended purpose. In other words, they act more like filters for viable options. For example, standards about sulphur emissions imposed by the state agencies replaced the former ones for all system actors in the Dutch waste management system (Loorbach 2007), and had a negative impact on the assessment of the incineration option by municipalities, as well as waste handling/processing companies. Similarly, the discharge limits imposed by the Swedish regulators are discussed to be important in shaping the transition away from the chlorine bleaching widely used in the pulp industry (Reinstaller 2008). These limits redefine what is acceptable, and what is not in terms of the main processes in paper production.
References of an actor can also change as a consequence of the actor’s interaction with the options. An actor’s experience with a certain option to fulfil a need conditions/shapes the expectations of the actor regarding the way that need has to be fulfilled. With a simplified depiction, the expectations of the actor converge to what the currently utilized option delivers, and this option sets the comparative reference point. For example, cost and ease of use are two relevant issues in assessing electricity supply options. The potential users did not have a precise expectation about the normal price of electricity when it was invented. Such a reference shaped over time, as it is the case in many other technology-user interactions as well (Schot and de la Bruheze 2003). Being the dominant option for a long time, centrally-generated grid-based electricity shaped such expectations about the cost of electricity, which is now being used for assessing the alternative electricity supply options. Nykvist and Whitmarsh (2008) discuss similar experience-driven expectation formation processes in the context of mobility. These references, which are formed and reshaped by individual experiences of the actors, get stronger and deeply rooted as experience accumulates.

Social influence can also be an important driver of reference formation and change. Apart from what is dictated to, and experienced by the actor, the practices (and references used) in the social sphere of the actor set an example about the way things might/should be done. The temperature of water for a ‘proper’ laundry, for example, influences the expectations of the actors about the features a new laundry option should deliver (Shove 2003). The reference point that defines the proper temperature can develop via social learning. Similarly, the average yield of other farmers in the same region shape a farmers assessment of the alternative farming practices (Cowan and Gunby 1996).

Furthermore, it can be claimed that the developments of the references are hard to reverse. Once an actor adopts high expectations, it may require significant time to change it.

ii. Commitment formation

In the face of novelties in the options, or in the environmental conditions, the decisions of the actors are not always history-independent. These decisions can be very much influenced by the former course of actions of the actor. A commitment to a certain course of action (e.g. investing in a certain technology, using a certain computer operating system) can develop as a consequence of decisions in the past, and the tangible and intangible assets acquired as a result of these decisions. Eventually, such a commitment can yield to a resistance against shifting to an alternative course of action, even in the cases where the new action is economically rational thing to do, for example. This phenomenon has been raised by various authors in the context of socio-technical systems; Hughes (1983) mentions the investments into the direct current system as discouraging a shift to the polyphase system. Rosenberg (1982) talks about the slowness of the behaviour change due to the existing stock of capital. Finally, Levitt and March (1988) coin the term ‘competency trap’, which can be summarized as accumulated experience with an inferior procedure inhibiting the shift to a superior procedure in organizations.

The commitment issue, and specifically the escalation of commitment phenomena, has been studied in the decision-related fields for long (Kiesler 1971; Pala 2008 for an extensive review; Staw 1976). Although competing hypotheses have been proposed to explain processes underlying the phenomena (e.g. sunk costs (Garland and Conlon 1998), or self justification (Staw and Fox 1976)), it is agreed upon that some actions lead to commitment, whatever the
underlying psychological or cognitive processes are. However, not all decisions contribute to commitment formation at the same level, if they do at all. In the broadest sense, a commitment-forming decision yields to consequences that are relevant for the subsequent decisions of the actor. For example, past experience with a computer operating systems (e.g. Linux, Windows, Mac OS) yield to acquaintance of the user with that particular operating system. This acquaintance is relevant for the future choice of the user, since the user is expected to be more comfortable with the old operating system, everything else being equal for the alternative operating systems. Therefore, the past experience of the user can be claimed to form a commitment to a particular operating system. As a contrary example, consider the choice of an actor with respect to organic versus regular farm products (Belz 2004). Historical consumption of an actor can be claimed to have minimal, or almost no relevance for the prospective grocery decisions; i.e. former consumptions of organic food does not make the user's future experience with this kind of food easier or more enjoyable. In that respect, this choice does not have a clear commitment formation impact as the previous example.

The accumulations of the consequences of the actor decisions (e.g. allocation of physical or economical resources, or effort spent on an option) are important sources of commitment in the socio-technical systems. These accumulations can be considered as assets acquired by the actor in relation to an option, and these assets can be tangible, as well as intangible in nature. Funds spent on R&D activity, or buildings and machinery owned are tangible asset examples. During the Dutch transition from coal to natural gas as the primary source of energy (Correlje and Verbong 2004), the inertia of the oil-based industry in shifting to the natural gas can be attributed to their commitment to the oil option due to their already existing infrastructure and capital investments; typical tangible assets. Intangible assets can also be as important as tangible ones in forming commitment. Expertise, know-how, and acquaintance are some examples of intangible assets that result from the actions of the actors in the past. These intangible assets develop over time mainly as a consequence of the experience of an actor with a technology or an artefact, as a researcher, a user, or an investor. The writing speed with a keyboard layout is a direct consequence of accumulated writing experience, and can be an important commitment-forming factor. Formation of a this type of intangible commitment is claimed to play a critical role in the global lock-in to the QWERTY keyboard layout (David 1985). Current lock-in situation experienced with respect to computer operating systems, Windows being the dominant one, is also partially due to similar sort of commitment formation due to accumulated know-how.

In the case of transition in the naval transportation in UK from sail- to steam-ships (Geels 2002a), it is possible to talk about both tangible and intangible assets; the sail-ships in operation, and the experience with operating these ships, respectively. The commitment caused by these assets was an important reason behind the resistance of these companies in shifting to steam-ships, and rather focus on improving the sail-ships against the competition of the steam-ship option.

### iii. Preference structure change

The preference structure of an actor indicates the important issues for the actor in assessing the available options, as well as the relative importance (e.g. weights) of these issues. In other

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3 The network externalities, i.e. compatibility of documents and applications, and complimentary services, i.e. software, are other important factors.
words, this structure specifies *which issues the actor cares about*, and also *how much the actor cares about these issues* in the context of fulfilling the relevant societal need. In the short term, the preference structures of the actors can be assumed to be stable and fixed. However, considering the long time horizons very typical in transitions, such an assumption is difficult to justify (see Geels (2005b), and Whitmarsh and Nykvist (2008) for similar discussions). Therefore both changes in the set of issues, and in the relative importance of the issues should be considered in analyzing transition dynamics.

A change in the preference structure of an actor can be attributed to a variety of processes. The most prominent mechanism in the transition-related literature is the problem-induced priority change, which is discussed by various authors (e.g. Belz 2004; Hughes 1983; Mozdzanowska and Hansman 2008; Nykvist and Whitmarsh 2008; Rosenberg 1994). Such a change is a consequence of the awareness about a problem, which can be directly related to the way socio-technical system functions, or to the consequences of the mode of functioning. In other words, the preference change is induced by a problem that is local to the system of concern. Such a problem directly related to the way the system functions can also be labelled as a *regime problem*, using the jargon of the transition field. In the most general form, the problem is a mismatch between the expectations or standards of the actors, and the related system indicators (e.g. noise levels, pollutant emissions, traffic density). This mismatch can trigger a change in the related priorities of the actors in order to alleviate the problem.

The problem that induces change need not be local to the system of concern, but also a problem with a wider scope can induce preference structure changes. These problems with a wider scope can be considered *quasi-independent* from the socio-technical system in focus in most cases; i.e. the problem would be there even if the particular socio-technical system was functioning in a totally different way. In this case, the problem can be labelled as a *landscape problem*. A landscape problem can also trigger a change in the preference structures of the actors. For example, climate change is a conjoint consequence of the way numerous socio-technical systems were functioning over decades. In that respect, the problem can be seen as a landscape problem for the Dutch mobility system. Scientific information that links this landscape problem to carbon emissions makes the problem relevant in the context of the mobility system, which functions in a carbon-intensive mode. This in turn lead to changes in the preference structures of both users and regulators, making issues like fuel efficiency and emission rates relevant for the actors, and increasing their relative importance compared to other issues. Popular science publications such as *Limits to Growth* (Meadows, Meadows et al. 1972), and *Silent Spring* (Carson 1962) played a key role then in raising global awareness about the unsustainability of the material-intensive economic growth and long-term consequences of chemicals used in agricultural activities, respectively. Such awareness can be claimed to be responsible for increasing priority of environmental friendliness in the northwest Europe during the last three decades, for example.

Although it is the most frequently discussed case in the context of socio-technical transitions, a preference structure change need not always be induced by a problem, be it a regime or landscape problem. For example, cultural, economic, or institutional landscape developments can also play an influential role on the priorities of the actors. As in the case of landscape problems, landscape developments are also quasi-independent from a particular socio-technical system, and these have consequences on wider scales. However, they can influence
the preference structures of the system actors, and interfere with the way the particular socio-technical system functions. For example, a shift from a collectivist society to a more individualistic one can increase the relative importance of an issue such as self-sufficiency. Such a priority change would have changed the decisions of the actors in numerous socio-technical systems. Similarly, a global liberalization wave can alter the dominant guiding principles of a regulator, or even the individual companies operating in a specific socio-technical context. Such an example of liberalization altering the preference structure of actors in the Dutch energy context is discussed in Chapter 10 in more detail. Although such an external influence on the preference structures can be important in transitional change process, it does not qualify as a mechanism in the way it is stated above; the conditions which trigger it, and the chain of events/processes that links the trigger to a preference change are not well specified based on the inductive analysis of the case studies. Most probably such mechanisms can be identified in cultural studies, for example. However, extending the empirical and theoretical basis of this study into those domains goes beyond the scope of this study. Therefore, the existence and the potential role of this sort of externally influenced preference change are acknowledged without further specifying responsible mechanisms.

5.6. Mechanisms driving complex dynamics

The mechanisms introduced in the previous section are very simple, and linear processes, as they are aimed to be. However, the transitional changes are characterized as complex and non-linear processes of change. This brings about the questions on to what degree and how these simple mechanisms can serve the purpose of analyzing such dynamic complexity.

The mechanisms can be very simple individually, but within a socio-technical system these mechanisms do not operate alone and in an isolated manner. It is appropriate to see the system as a web of such simple mechanisms that are connected to each other (i.e. the consequences of one mechanism can be the trigger for another one), and are concurrently active. This interlinked set of simple mechanisms creates a feedback-rich and non-linear structure that is capable of generating complex dynamics observed typically in socio-technical systems. Especially the existence of multiple actors and multiple options in the system increase the complexity of this web.

An example may clarify the point mentioned above. For the sake of simplicity, leave aside a complete transition context, and just consider the adoption of a new gadget (e.g. e-reader) (see Figure 5.1). By some means, like marketing campaigns, it is possible to create an imprecise initial perception about the new gadget among the users of the old one (i.e. potential users for the new gadget). After this point, the dynamics to unfold will be determined by the conjoint result of a small set of mechanisms. The early adopters may learn that the gadget is unable to deliver what they were expecting very quickly (individual learning), and spread the news (social learning). In this case, the adoption might cease, and a backlash dynamics can be observed for the new gadget. There is not enough experience, or critical mass of users to trigger any significant development for the new gadget. In short, the new gadget will end-up as a short-lived fad. Alternatively, the technical properties of the gadget can be developed based on the experience gathered through the early adopters (experience-driven property change). Besides this, the adopter group may create a sort of network externality and make the gadget more attractive for others (scale-driven property change). If these developments outrun the learning processes that spread the news about the early deficiencies of the gadget, the gadget
may develop into an attractive one competitive enough to overthrow the previously dominant one. In this alternative case, it is possible to label the situation as a self-fulfilling prophecy: the initial belief among users that the gadget was attractive triggered developments that fulfilled this belief, eventually. Depending on the relative pace and strength of learning and property change mechanism, it is possible to observe dynamics that lie somewhere in between these two extreme ones. An in-depth analysis was conducted by the author using a quantitative simulation model for the depicted case (Yücel and van Daalen 2009b; Yücel and van Daalen In Press). The study demonstrates significant variations in the observed dynamics spanning the spectrum from the no-diffusion to full-diffusion cases, which are primarily conditioned by the role of interacting learning and option development mechanisms.

As a second example, we discuss the mechanisms in the context of a problem-driven change process. Consider a waste management context where incineration is one of the dominant ways of eliminating the waste (see Figure 5.2). From several perspectives (e.g. space needed, operation costs) incineration may be a convenient choice for the actors (e.g. municipalities) in their waste allocation decisions. However, exogenous developments such as scientific findings on health impacts of air pollution may change the situation. Once the actors learn the negative impacts, it may be expected that these actors will set/update the limits for tolerable air pollution levels (i.e. reference formation process), and will start evaluating the situation with respect to these tolerable levels. Meanwhile, the actors will be learning about the actual pollution levels through direct observations, or published reports. The situation when the pollution levels exceed the tolerable limits significantly may create a sense of problem in the system, and trigger a change in the relative importance of issues for the actors who become more emission-conscious (i.e. preference change processes). Following this point, two major development trajectories can be foreseen; either the actors phase out the incineration option from their waste-related decisions, or the incineration option develops in a way to address the increasing emission concerns in the system (i.e. option property development process). In the former case, another option will emerge as the dominant way of waste management in the long run, and in the latter case the waste will be managed through cleaner incineration yielding tolerable air pollution levels.
It should be kept in mind that the examples discussed above are fairly simplified ones to demonstrate how mechanisms can be interrelated, and how they combine and form non-linear feedbacks in the system. In a more realistic depiction, very similar processes would be active for other alternatives, including the previously dominant one, and the variety of actors in the system would be higher (e.g. different end-user groups, providers, etc.). In summary, the simple mechanisms introduced previously, which are not complex themselves, constitute the atomic pieces that can be used to reconstruct the complex internal web of the socio-technical systems.

![Interlinked mechanisms in the problem-driven change example](image)

**Figure 5.2. Interlinked mechanisms in the problem-driven change example**

### 5.7. Conclusions

In this chapter, we introduced a fundamental component of the *actor-option framework; mechanisms of change*. The *mechanisms* that are discussed constitute generalized forms of basic processes through which *options*, and *actors’* behaviours with regard to these *options* change over time. In that respect, they are the building blocks of internal dynamics of a socio-technical system when it is analyzed based on the *actor-option framework*.

Based on the general scheme of interaction between *actors* and *options*, which is discussed in Chapter 4, we clustered the *mechanisms* into three groups. The first set of *mechanisms* is related to the ways *options’* properties, be them embodied or disembodied, may be changing over time. The second set is about the *actors’* perception of their environment, and how they get to know changes in this environment (e.g. changes about available *options*, the whole system, or other *actors*). This set of *mechanisms* relate to what is referred to as first-order (or single-loop) learning. The third, and the final, set of *mechanisms* are related to *actors’* behavioural identity; i.e. the factors that influence the way an *actor* evaluates the available behavioural choices. More specifically, these mechanisms are related to *actors’ references, preferences, and commitments*. Since this final set of *mechanisms* is related to changes in the way actors behave in a given situation, they can be considered as second-order (or double-loop) learning processes.
The mechanisms are proposed as simple building blocks of complex transitional change processes. They are individually simple and easy to comprehend. However, once even a modest set of these mechanisms are interconnected, they create a system structure that is rich in non-linear feedbacks; i.e. a structure that can create complex dynamics that is very difficult to comprehend. In Section 5.6, we provided two elementary examples in order to demonstrate this 'complexity build-up by simple mechanisms' issue.

According to the actor-option framework, the proposed set of mechanisms constitutes the motor of change. In other words, these mechanisms are the drivers of dynamic system behaviour in a model that is developed to analyze/explore transitional dynamics of a socio-technical system. However, these mechanisms are not proposed in the form of a single general model of transitional change. Instead, they constitute a portfolio of general processes to be used as building blocks of problem-specific models. In other words, the mechanisms should be considered as modular pieces for model conceptualization (i.e. pieces of a dynamic hypothesis), rather than a ready-to-use conceptual model.

As discussed earlier, these mechanisms are formulated at a generic and abstract level. This level of abstraction makes it possible to use them in a variety cases from different socio-technical contexts, as conceptual constructs that assist the analyst to identify transition-relevant aspects.
Positioning the Actor-Option Framework

6.1. Introduction

Although the actor-option framework is not a general hypothesis on how transitions unfold, per se, it provides modular conceptual units for developing generic and case specific dynamic hypotheses. In some sense, it is an addition to the conceptual models and the explanatory attempts that have been proposed in the field. In that respect, it is important to compare and contrast the actor-option framework with such previous efforts in order to identify the extent of the contribution of this framework better.

As discussed earlier in Section 1.4, there are two different views about the regime/niche concepts within transition studies. According to the first interpretation, a regime/niche constitute conceptual boundaries (or a social field) in a transition analysis; i.e. conceptual boundary perspective. Dynamics are analyzed referring to the developments taking place within these boundaries. The second interpretation treats a regime/niche as an emergent social entity, which possesses properties different from those possessed by its constituents. Analyses using this latter perspective, i.e. emergent entity perspective, mainly rely on the changes of these emergent entities, rather than changes related to their constituents. The discussion on the relation of the actor-option framework with the current state-of-the-art in analytical transition studies will address these two perspectives separately, for the sake of clarity.

6.2. ‘Conceptual boundary’ perspective

Geels and several co-authors of his dominate the cluster of studies that propose and develop this perspective as a general way of analyzing transitions. Research efforts associated with this perspective are generally descriptive in nature, and motivation for identifying a generative explanation is limited. In a broad sense, this constitutes the biggest difference between the actor-option framework and this cluster of transition studies. Saying that, there are also some contributions that aim to explain how transitions unfold over time in this cluster. Especially, three of these contributions are closely related to the proposed framework. These are related
to conditions that create windows of opportunity for transitions (Geels 2005b), mechanisms that drive transitions (ibid.), and pathways as different manifestations of transitions (Geels and Schot 2007).

a. **Conditions creating windows of opportunity**
Geels emphasizes the ‘window of opportunity’ concept as the result of contextual conditions that create a suitable climate for a transition. The conditions that may contribute to creating such a window are various. As a preliminary set of such conditions, Geels proposes a non-exhaustive list of conditions;

- External problems, such as environmental negative externalities
- Internal technical problems in the existing regime that cannot be solved by the available technology
- Changing user preferences
- Strategic and competitive games between firms that can speed up the development of the new technology
- Availability of complimentary technologies for the new technology

Despite having some descriptive value as they are, such conditions need to be supplemented by other pieces in order to be able to explain transition dynamics. Seeing all these conditions as exogenously developed and imposed on the system is a narrow perspective, and overlooks the relation of these conditions with the internal dynamics of the socio-technical system. One of the missing pieces is about the internal dynamics of the system that lead to these conditions. Second missing piece is about the developments following the appearance of a condition; once a particular condition develops, what are the following implications for the system? More specifically, which processes are triggered by such conditions? The mechanisms proposed in the actor-option framework compliment the conditions in both of these aspects.

This complimentary aspect can be recognized clearly on a particular example, such as the transition experienced in the Dutch waste management system (Loorbach 2007). An important trigger of the changes in the waste management practices were space problems for landfilling sites, and the recognition of landfilling-related ground water and soil pollution. All these can be considered as examples of external problems\(^1\) (environmental externalities) of Geels. Perception of these conditions by the system actors triggers a change in preferences towards more environment-friendly practices; i.e. resulting in a condition of changed preferences. Under such conditions, a competition between landfilling and incineration starts. However, landfilling practices have little room for development in environmental or space-related issues (i.e. internal technical problem). This condition inhibits the mechanisms of option development, and influences the way this competition unfolds. This simplified storyline demonstrates how mechanisms create conditions, and how these conditions trigger further mechanisms of change. In summary, the mechanisms of the actor-option framework provide a dynamic explanation for the development of conditions that create windows of opportunity, as well developments that follow these conditions. Additionally, the overall framework structure, as a depiction of major processes driving transitions helps to identify further conditions that can trigger transitional change. A quick investigation of Figure 6.1, for example, shows that an abrupt change in the information possessed by system actors (e.g. availability of a new scientific report) may trigger further changes in the system, and can yield a condition that creates a window of opportunity.

\(^1\) It is also possible to see the space-related problem as the internal problem of the landfilling practice.
Besides, ‘strategic and competitive games’ discussed by Geels are not explicitly described in the discussion of the conceptual framework in this dissertation. However, depending on how actors’ behaviours are specified, such games can easily be covered within the conceptual framework.

b. Mechanisms of Geels
The multi-level perspective (MLP) is discussed in Chapter 1 as a framework that serves well in structuring transition narratives. It is also mentioned that MLP does not provide specific clues about the processes that underlie transitions. In some sense, MLP puts three domains of change (i.e. macro, meso, and micro levels), but leaves these domains empty in terms of transition-related processes taking place within them. Recognizing this aspect, Geels points out the need for ‘filling the MLP’, and makes a preliminary effort in that direction by proposing a set of mechanisms. The set of Geels consists of the mechanisms identified in historical transition cases; i.e. a list compiled through an inductive search. Although the effort is important, it is pre-mature and insufficient to constitute a basis for building generative explanations for transition dynamics.

First of all, Geels’ mechanisms are underspecified: conditions that trigger these mechanisms, the way these mechanisms operate, and the ways multiple mechanisms interact are not specified. Considering Geels’ objectives, it is clear that a detailed specification is not aimed there, but such a specification is required if such mechanisms are to be used as explanatory mechanisms. In that sense, Geels’ mechanisms, and the mechanisms proposed within the actor-option framework differ in the objective they serve.

Secondly, it is not very clear if Geels’ mechanisms are drivers of change, or consequences of such drivers yet to be identified. Some of those so-called mechanisms can be considered as conditions that have been observed in successful transitions. In that sense, although the same label, i.e. mechanism, is used for both, it is clear that the mechanisms of the actor-option framework and Geels’ mechanisms are fundamentally different things. As a result, it is difficult to talk about an overlap, which is hinted by the naming conventions used in these two studies.
It is argued that the mechanisms of Geels are dissimilar to the ones introduced in this study. That is being said, the actor-option framework may be used to enhance the mechanism set of Geels. The original set is identified investigating a number of case studies. The actor-option framework makes it possible to look for new mechanisms via experimental search: the framework can be used to develop generic system configurations (e.g. multiple niche technologies, no user group diversification, etc.), and supported by simulation models, such configurations may be used to search new mechanisms in successful artificial transitions.

### Transition pathways

*Paths*ways are proposed by Geels and Schot (2007) as different manifestations of transitions. Four main pathways, i.e. stereotypical transition narratives, are as follows:

- Transformation
- De-alignment and re-alignment
- Technological substitution
- Reconfiguration

These different manifestations constitute the type of dynamic variety that the actor-option framework is developed to explain and understand. For example, in which system configurations and under which conditions a ‘de-alignment and re-alignment pathway’ is more likely is a typical question to be attacked using the actor-option framework. In short, the framework provides conceptual tools to delve into the processes behind pathways, and deepen the current state of understanding about these different transition manifestations.

As was previously claimed for conditions and mechanisms, the framework coupled with simulation experiments can also be used to develop and enhance the set of pathways via adding new ones, or revising the existing ones. For example, one of the recent work utilizing the actor-option framework provides an example of such possibilities (Yücel and van Daalen 2009b): the simulation experiments with a generic model, which is used to explore different circumstances in terms of a regime and a niche-innovation, reveals transition dynamics that do not fit into the already defined pathways, such as the step-by-step transition (or terraced transition).

#### 6.3. ‘Emergent entity’ perspective

The second conceptual perspective treats regime/niche concepts as emergent social entities. Being emergent, these entities are assumed to possess properties that are different from the ones possessed by individual constituents of these emergent entities (e.g. actors, firms, organizations). This perspective sees the regime/niche, and their behaviours as building blocks for explaining transition dynamics. Furthermore, it is unnecessary to refer to lower level constituents of the regime/niche in such explanatory attempts, according to this conceptual perspective.

Two recent studies that adopt this perspective show significant overlap with this dissertation both in terms of the objectives, and also in the prescribed approach for analyzing transition dynamics. The first of these studies is the pillar theory (PT) of de Haan (2010), which is an attempt towards laying down a coherent and generic theory (or a conceptual model) on transitions. The second one is the modelling framework developed for the MATISSE project (Haxeltine, Whitmarsh et al. 2008), i.e. MATISSE conceptual framework (MCF). It is very closely related to de Haan’s work, and mainly builds on the concepts of PT.

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2 In the sense of the word used by Geels
Similarities and differences of the actor-option framework with these two studies are briefly discussed below. Due to the shared conceptual foundations and the perspective, most of the points that are discussed in relation to PT also apply to MCF. A shorter discussion specifically on this latter work that focuses on the novel aspects of MCF follows this main discussion.

a. Pillar theory

The three pillars of de Haan, i.e. *conditions, patterns* and *paths*, are the main components of the proposed theory on transitions. Since the ultimate goal of the pillar study is to provide a generic explanation on transition dynamics, it shows significant similarity with the actor-option framework in that sense. Despite this similarity in the general objectives on explaining transition dynamics, these two studies build on very different perspectives regarding where to look for such an explanation.

PT assumes that it is sufficient to reside at the abstraction level of the regime/niche in the quest for an explanation. In other words, the dynamics of these emergent entities, and their interactions are drivers of transitions according to the perspective of PT. On the other hand, the bilateral interactions of the social and the techno-physical aspects of a socio-technical system are seen as the driver of change according to the perspective of the actor-option framework. As a consequence, the latter uses a conceptualization of the system with a higher resolution, and focuses on the constituents of the regime/niche. Especially the variety among these constituents (e.g. social groups that are likely to follow different development paths) is of primary importance for the actor-option framework. This difference marks the fundamental difference between these two approaches in their attempts to explain transition dynamics.

The aforementioned perspective difference leads to different conceptualizations, but they are not necessarily inconsistent or conflicting. It is somehow similar to using two different languages to describe the same situation. It is possible to map one way of system conceptualization into the other way. For example, *pressure* is one of the *conditions* of PT, and is defined as the condition ‘when competitive alternatives to the regime appear in the niche-level.’ It is possible to depict a system in which pressure is observed with the actor-option framework. In the opposite direction, the state of a certain system configuration based on the actor-option framework can also be described using the conditions of PT. In short, it is possible to map these conceptualizations into each other. An important issue regarding this mapping is that it is not a 1-to-1 mapping; a *pressure* condition corresponds to numerous system depictions in the actor-option framework, whereas a certain system depiction in the actor-option framework corresponds to a single description in terms of *conditions*, i.e. it is a 1-to-M mapping. This discussion also holds for the *patterns*; a change that corresponds to a certain pattern may happen through different interactions of different sets of mechanisms introduced in the actor-option framework. This mapping issue will also be relevant with respect to another point during the comparison of the two approaches.

PT provides important pieces for explaining transitions. However, it lacks some key aspects that are necessary for constructing a coherent generative explanation. Primarily, the link between the *conditions* and the *patterns* is not specified in PT. Which conditions lead to which pattern? In case there are intermediary processes, which *conditions* trigger certain processes that yield to particular *patterns*? How does a particular *condition* arise, or disappear? These sorts of questions point out the aforementioned void in PT, if it is to be used to develop
generative explanations. Furthermore, it may be difficult to fill this void for PT due to the very perspective it is based on. Due to the high abstraction level, the variety of empirical cases that correspond to a particular condition, or to a particular pattern is vast. As a result, it may be difficult to postulate well-specified links between conditions and patterns; i.e. the possibility that any condition can lead to any pattern. The conceptual perspective is likely to prevent PT to establish the missing link. Saying that, such a link is not necessary for descriptive narratives. Therefore the aforementioned void does not harm the benefits of PT in that respect. However, the void makes PT inappropriate for the objectives of this study.

The more detailed conceptualization perspective of the actor-option framework is mainly adopted in order to avoid the aforementioned problem. At the abstraction level used with the actor-option framework, a particular system specification constrains the behaviour possibilities to a great extent. This enables linking the system configuration with processes to be triggered in such a situation (i.e. active mechanisms). Additionally, in the way mechanisms are defined, the aspects of the system that are changing through these mechanisms are easily identifiable. This enables tracing the way system changes as a consequence of such processes.

While contrasting the different perspectives of the two approaches, mainly the disadvantages of the low-resolution conceptualization of PT in constructing generative explanations are discussed. On the other hand, such a conceptualization also offers some benefits: the simplicity of the system depiction may make such a conceptualization easier to use for general discussions, and for descriptive narratives. A conceptualization of the system with a large number of interwoven mechanisms, which would be developed using the actor-option framework, may be more difficult to communicate for such purposes.

As already discussed, the building blocks for explaining a transition process are the patterns for PT, and the mechanisms for the actor-option framework. The way these building blocks are used marks another fundamental difference between these two approaches. PT depicts a transition as a linear sequence of patterns. A pattern leads to new conditions (i.e. a new system state), and following this new condition another pattern is observed. This goes on like this, and the resulting chain is named as a path, i.e. a particular manifestation of a transition. This 'linear sequence of patterns' perspective is an oversimplified way of looking at a complex dynamic process such as a transition. It can be claimed that this perspective overlooks the dynamic complexity of the process. According to the actor-option framework, a transition unfolds the way it does as a consequence of simultaneously active mechanisms, according to which system actors interact and/or system state changes. According to this perspective, an explanation for the observed dynamics should be sought in the conjoint impact of these atomic processes, and not in their individual impact. Therefore, 'one change at a time' perspective is unlikely to provide the required insights for such a challenge.

b. MATISSE conceptual framework
A conceptual framework for modelling transitions is proposed in the scope of the EU-funded MATISSE project; i.e. MATISSE conceptual framework (MCF) (Haxeltine, Whitmarsh et al. 2008). The objective of MCF is stated as to guide implementation of models that can reproduce transition pathways. Despite the proximity in the overall objectives, MCF and the actor-option framework differ with regard to the major concepts upon which these frameworks built. As PT, MCF is based on emergent concepts of regime/niches, and aim to explain transition
dynamics in terms of these concepts' behaviours, and interactions between these concepts. Therefore, most of the issues raised above while contrasting the dominant perspectives in PT and the actor-option framework also apply here.

One key component of MCF is the set of mechanisms that are ‘important to the core dynamics of a regime change’. These mechanisms, which are triggered by events and operate simultaneously, are the drivers of change for regime/niche entities in MCF models. In this respect, both the terminology used (i.e. mechanism), and the perspective on the role these mechanisms play (i.e. processes of change for the models’ building blocks) are very similar with the case of the actor-option framework. However, when studied in further detail some major differences regarding the nature of these mechanisms, the way they are identified, and the way they are included in individual models are observed.

First, the abstraction levels of the mechanisms are naturally different. MCF mechanisms operate at the level of the regime/niche; e.g. transformation into empowered niche (for a niche), adjust internal structure (for a regime), attack the regime (for an empowered niche). These mechanisms are claimed to approximate the outcome of the behaviours of many individual actors (ibid.), but no solid validation effort exists so far for supporting this claim. In other words, clear answers are lacking for relevant questions such as; does aggregation of what individual actors would do under a particular condition correspond to what a MCF regime does? On the other hand, the mechanisms in the actor-option framework operate at the level of options and actors. This makes the latter easier to link up to empirical observations, and enables straightforward validation and specification.

Secondly, the mechanisms in the actor-option framework are identified via induction based on case studies, as well as existing theoretical work. They are the outcomes of a search to identify what are the processes that change actors’ behaviours and options’ properties. However, the identification process for MCF mechanisms is not documented very clearly so far. In the way it is discussed, the search seems to be driven by the question of what is needed to reproduce certain transition pathways. In that sense, the appropriateness of MCF mechanisms lie in their replicative success independent of their success in resembling the actual system’s structure being studied.

Final difference arises at the stage of implementation, and relates back to the second issue discussed above. In both approaches, while developing a model, a subset of mechanisms needs to be selected and included in the model. In MCF, this selection is driven by the observed transition dynamics; which set of mechanisms is enough to imitate the observed transition? In the actor-option framework it is the internal structure of the socio-technological system that conditions the selection process; e.g. which mechanisms may be changing the properties of a particular option during the time horizon of the analysis? Saying that, it should be noted that the MCF approach is also acceptable as a generative explanation for the phenomena being studied. However, the appropriateness of such a model is questionable for conducting what-if kind of analyses.

6.4. Conclusions

In this chapter we considered the actor-option framework with respect to its relation with the existing conceptual perspectives/frameworks that aim to describe and explain transition
Chapter 6

Since the actor-option framework is not based on the levels of MLP (i.e. micro, meso, macro), it stands as an alternative to the multi-level perspective (MLP) in looking at systems in transition. Despite this, the complementary nature of these conceptualizations should not be overlooked. MLP provides a structure to frame a transition analysis, but tells little about the content of the levels (e.g. structure of the system at the meso level, or processes of change that is taking place in a certain level). In a sense, the levels of MLP are empty. Some conditions that indicate windows of opportunity, and resulting transition pathways are proposed to supplement MLP. However, dynamic processes that link these conditions to each other, and also to the resulting transition pathways are lacking. The actor-option framework can easily be seen as an effort towards filling the levels of MLP. The internal system structure at each level can be depicted in terms of actor-option configurations, and the mechanisms of the actor-option framework depict the change processes taking place in these levels. In short, the actor-option framework complements MLP in explaining the emergence of the conditions, as well as the development of transition pathways.

When we compare the actor-option framework with the pillar theory (PT) and the MATISSE conceptual framework (MCF), a significant overlap in the overall objectives (i.e. explain how and why transition dynamics unfold in the way they do) is observed, as well as important differences in the way they try to achieve these objectives. First of all, PT and MCF both are based on a high abstraction level, and use regime and niche concepts as the building blocks of analyses. These concepts are treated as social black boxes in PT and MCF. The actor-option framework, on the other hand, relies on the constituents of these black boxes, and builds the analyses on atomic concepts that correspond to social (actors) and techno-physical (options) aspects of the system. In a sense, these two approaches can be seen as two different conceptual languages that try to explain the same phenomena.

The high abstraction level of PT and MCF brings simplicity to descriptive narratives, and ease in general conceptual discussions. However, once the specificity of the analysis increases, the abstraction level can be problematic. Firstly, it is hard to relate empirical information to this high abstraction level. Secondly, it leaves too much room for subjective interpretation in linking case-specific detailed information to the abstract concepts of regimes and niches. Same difficulty also holds for translating back the insights developed based on such abstract concepts into a specific policy-making context. The level of abstraction used in the actor-option framework, as well as its basic conceptual elements makes it easier to empirically link a conceptual model to a specific transition case. In that respect, all three conceptualizations may be appropriate for generic analyses on transition dynamics, but we consider the actor-option framework to be more appropriate and rich for analyses that are case-specific.

A fundamental difference between PT and the actor-option framework is related to the way a transition process is depicted, in general. In PT, a transition is depicted as a linear chain of patterns. This linear way of conceptualization, i.e. seeing a transition as a sequence of developments is quite different from the fundamental perspective behind the actor-option framework. According to the latter, a transition is a consequence of a set of dynamic processes that are active simultaneously. It is not their sequence, but the way they interact (e.g. reinforce and/or counteract each other) is the source of complex dynamics observed in a transition according to the actor-option framework. Therefore, it is this interaction what is aimed to be understood.
Besides these issues that differentiate the *actor-option framework* from PT and MCF, there is also potential for some synergy, especially related to the processes that drive change. PT proposes some *conditions*, and resulting *patterns* that can be used to describe transitions in a sequence of phases. However, it lacks the link between conditions and patterns; the processes through which a condition leads to a particular pattern. Deduction of such links can be challenging. However, the mechanisms of the actor-option framework can be used for analyzing plausible dynamics under given conditions, and help to link conditions to patterns in an inductive manner.

MCF already addresses the issue of linking conditions to patterns, and specifies some mechanisms triggered by conditions and give rise to patterns. However, these mechanisms are difficult to empirically test for their presence. In a way, they are not validated in a convincing manner so far. The *mechanisms* of the *actor-option framework* actually correspond to the micro-level processes whose aggregate consequences are being approximated by the mechanisms of MCF. In that respect, the actor-option framework can be used to validate the proposed processes of change in MCF, hence strengthening the foundations of that conceptual perspective.

In conclusion, firstly, the *actor-option framework* stands as a novel conceptual perspective, a different way of looking at the system in analyses of transition dynamics. The abstraction level of the framework, which makes it easier to establish empirical links with a real-world policy making context, seems to be an important difference of the framework from the existing perspectives. Additionally, since the goal is to explain the unfolding of transition dynamics, the content of the framework is not confined to descriptive concepts that depict the state of the system, or the consequences of a process; the framework covers processes of change that explain the internal changes in the systems, which seems to be immature in the existing perspectives. More importantly, besides constituting an alternative to the existing conceptual perspectives, the actor-option framework also has a very important potential to complement those perspectives.
The actor-option framework was introduced in Chapters 4 through 6. The framework is proposed as a general (i.e. context independent) conceptual grounding for simulation-supported analyses of transition dynamics in socio-technical systems. There are three basic premises of the framework, on which it has been developed. These basic premises are as follow:

- The behaviour of social actors are key to understanding transition dynamics, and should be an explicit part of explanatory models (Actor representation premise)
- Components of a socio-technical system that have different character in terms of the ways they change over time should not be aggregated in the conceptual models that aim to explain the unfolding of a transition process (Disaggregation premise)
- The conceptual models should reside at an abstraction level that allows direct correspondence with real-life policy measures (Policy-relevant abstraction premise)

This part of the dissertation deals mainly with the exploration of the usability of the framework as a general conceptual basis, as well as with the investigation of the relevance of its basic premises. In order to do so, three modelling studies have been conducted on different transition cases using the actor-option framework. These modelling studies are discussed in Chapters 8 through 10. Two of these cases are about historical transitions; the waste management transition in the Netherlands, and the transition to steam-ships in the British naval transportation system. The third case is about the recent developments in the Dutch electricity supply system, which can be considered as an example of an ongoing transition. The last chapter in this part of the dissertation, Chapter 11, provides a general reflection on the framework, and the extent of its usability based on the three modelling studies conducted. In the following section, we briefly discuss the case selection criteria, and we further elaborate on the aspects we investigate regarding the framework during these three modelling studies.
a. Case selection
An important criterion for the selection of the cases was the availability of qualitative and quantitative information. Accordingly, we have selected the historical cases among the comprehensive transition case studies in the literature, which provide rich historical accounts of the developments during the whole transition process. The third case, i.e. Dutch electricity supply, is also considered as appropriate in terms of information availability; it is possible to access detailed technical and economical information about the system and its components with relative ease, especially about the period posterior to the liberalization of the markets.

A second criterion in our case selection was to have variety in the set. First of all, the cases have been selected from different contexts, as will be discussed further below. Secondly, the selection has temporal variety, as we consider one historical, one more recent, and an ongoing transition. Finally, the main characteristics of the selected cases also differ. In the waste management case (Chapter 8), the transition develops around environmental problems, and the changing perception of the actors towards the waste issue. The role of technological developments is insignificant compared to these. The general character of the naval transportation case is quite different; the major developments are related to the emergence and development of a novel transportation option. In other words, technical and economical processes have leading roles in the case, as will be discussed in Chapter 9. Despite being an ongoing process, all these social, technical and economical aspects have the potential to be important in the electricity supply system case; hence the case has a more comprehensive scope compared to the former two (Chapter 10).

b. Investigating the framework, and the basic premises
During the modelling studies, we explore the feasibility of the actor-option framework as a general conceptual basis for analyzing transition dynamics. An important aspect about the framework is the generality claim, and this is one of the issues we investigate with these modelling studies. The cases are selected from different socio-technical contexts, as mentioned above. In assessing the framework with respect to the general applicability aspect, we evaluate whether the specific components of the systems in the case studies can still be represented using the general concepts (e.g. option) of the framework. For example, the means of fulfilling the societal function in focus, which are represented by the general concept of the option, are very different in nature in these cases. The question at this stage is if the option concept, and the mechanisms related to the way an option changes can be specified to represent the specific means of fulfilling the need in a particular context, and also the type of changes it can go through.

Furthermore, we use the modelling studies for exploring the limitations of the framework. We focus on two kinds of limitations; conceptual and practical limitations. Conceptual limitations are related to the difficulties encountered in representing particular issues and processes from the actual transition context using the conceptual elements of the framework. In the historical transition cases, ex post analyses are available of the important factors and processes that shaped the transition dynamics. For these cases, we investigated whether the actor-option framework provides the concepts and mechanisms that can be used to represent these important factors and processes, and also the difficulties in conceptually representing them.

For the third case, the Dutch electricity supply case, the situation is different since it is not an
already completed transition process. As it is an ongoing process, any judgement related to the relative importance of certain processes would be speculation. However, we investigated the sufficiency of the conceptual representations developed by the actor-option framework by comparing the model with a set of other models from the literature that cover different aspects of the electricity supply system in detail. In a way, instead of using an ex post analysis on important issues, we relied on benchmarking the developed model with the other recently developed electricity system models in investigating the conceptual limitations. Furthermore, we have selected this case in order to apply the framework in modelling a fairly complicated socio-technical system for analyzing its transition trajectories. Considering the technical, infrastructural and economical aspects, and the multiplicity of the actors involved, the case qualifies as an example of a system with a complicated internal structure. Using this case, we aim to investigate the limitations related to the general concepts and mechanisms of the actor-option framework in representing this complicated internal structure.

Being able to develop a conceptual model does not necessarily imply that such a model can easily be translated into a quantitative simulation model. This is mainly an issue related to quantification and formalization of the concepts and relationships included in the conceptual models. Related to this issue, we explore the practical limitations (i.e. difficulties in representing the concepts of the framework in quantitative simulation models) that can be encountered during using the actor-option framework. These are limitations mainly related to the quantification of the concepts, and formalization of the mechanisms. Identifying such limitations constitutes another important objective in conducting the modelling studies discussed in this part of the dissertation.

Additionally, we also use the developed models in order to identify and illustrate a set of circumstances under which the three basic premises of the framework are relevant and important. This is done via investigating circumstances under which the basic premises are fundamental in explaining the observed transition dynamics. This way we aim to collect evidence that helps to justify the basic premises of the actor-option framework.

Before proceeding into reporting these assessment-oriented modelling studies, the following chapter introduces how to develop a model for a given transition case using the perspective of the actor-option framework. This brief introduction, which is presented in the form of a step-by-step workflow, covers identification of basic concepts within an empirical case, and also representation of these concepts in quantitative forms (e.g. relations, actions, etc.). Chapters 8, 9, and 10 are devoted to discussing the three models developed as proof-of-concept implementations. The last chapter, Chapter 11, is a general discussion based on these three modelling studies, and in this chapter we reflect on the actor-option framework, in general, referring to the experience and observations from the individual modelling studies.
7.1. Introduction

The actor-option framework provides a set of key concepts, which can be used to develop models for analyzing a transition problem. However, how to customize and combine these concepts in order to develop a case-specific model is left unspecified in the previous chapters. Such a specification may be unnecessary for analysts who internalize the perspective and the concepts of the framework. However, a concise set of guidelines is necessary for a proper utilization of the framework in a wide application domain. This chapter presents a structured description of developing a model with the actor-option framework, which is expected to serve as a set guidelines for model development.

7.2. Guiding questions for model development

The description is organized as a sequence of fundamental questions that need to be answered throughout the model development process. The questions are expected to help in specifying the boundaries of the system to be modelled, as well as the way internal structure of the system may be represented. Although following the sequence of the questions is not vital, this may prove useful in keeping the development process well structured.

a. What is the societal function/need of concern?

A transition is related to the way a societal function/need is being fulfilled. Therefore, an analysis starts with defining this societal function/need. The conceptualization of a model for analyzing transition dynamics is developed around this societal function/need. In some sense, the societal function is a kind of an 'anchor concept' relative to which other aspects of the model are identified. The clarity and the specificity in the definition of the societal function are very important, and make the model development process straightforward. A vague function definition is likely to hinder the model development during following stages. A clear and specific function definition helps define the boundaries of the socio-technical system, the spatial scope, and the time horizon of the analysis, among other things.
b. Which aspects of the societal function characterize the transitional change?

In a particular analysis, not all directions of change are of interest: generally it is a major change with respect to a certain aspect, or a set of aspects that is of interest. Identifying this set of aspects complements the societal function definition in guiding the model development process. These aspects are referred to as ‘transition-characterizing’ ones throughout the dissertation. For example, consider an electricity supply system. In an analysis focusing on transition with respect to fuel mix and emission levels, a wider utilization of decentralized combined heat-power units may not mean much progress. They simply represent more of the fossil fuel-based system. However, if the analysis is focusing on transition with respect to the control structure, such an increase corresponds to an empowerment of the de-centralized supply structure against the centralized one. As seen from the example, the same development can be considered either as pro-status-quo, or as pro-transition depending on the perspective of the analysis.

c. What are alternative means of fulfilling the societal function?

This stage of the process is about identification of the options that will be explicitly covered in the model. One important issue about the options is that they are not just technologies, or artefacts: the practice according to which a technology is used can also be a defining characteristic of an option. For example, car-pooling can be considered as an alternative mode of transportation for urban mobility. The artefact, i.e. the car, is not the only defining aspect of the option, but the way this artefact is used is also a crucial defining aspect for the option.

Depending on the scope and detail level of the study, an option may correspond to a family of artefact-practice combinations. In a very aggregate analysis on mobility, public transportation may be represented as a single option. In a more detailed analysis, trains, buses and metro may be represented as separate options, as well. The resolution level in developing the option set is dependent on the particular objectives and scope of the analysis. Moreover, the previously identified transition-characterizing aspects provide clear guidance in option-related aggregation choices. Alternative ways of fulfilling the social function that differ significantly with respect to the transition-characterizing aspects should be represented as distinct alternatives in the model. On the other hand, similar options can be aggregated into a single alternative in the model, depending on the resolution level of the analysis. For example, while studying a transition with respect to fuel mix, decentralized combined heat-power units and conventional generation plants can be aggregated into a general natural gas-based thermal generation option, in a highly aggregate analysis of electricity generation transition. However, when the issue is a transition with respect to the control structure those two should not be aggregated into a single option, but be represented as separate alternatives.

Finally, there are two sets of options, which are treated differently during a model-supported analysis. The first set, i.e. base set, includes the already available options, and the options that are expected to appear in the short term with some certainty. The second set, i.e. experimental set, includes the options that are speculated to appear in the medium to long run in the transition context being analyzed. While the base set is introduced into the base version of the model, the experimental set is to be treated separately and considered during scenario experiments.
d. Who are the major social actors in the system?

This stage is about determining the social coverage of the model, i.e. actors. The ‘who’ question raised in the heading is supplemented by a ‘how’ question (i.e. how to represent the system actors in the model?) in order to guide the efforts related to this stage of model development.

The actor-option framework proposes four actor-roles (i.e. users/practitioners, providers, regulators, and opinion groups) as different aspects of the social sphere related to the societal function. These roles provide some guidance for looking into the real system and identifying relevant actors (e.g. individuals, organization, companies) in the socio-technical system being studied.

As in the case of the options, some representational decisions need to be made regarding the actors. Despite being technically feasible, a 1-to-1 mapping between the model and the real actors can easily give rise to a practically useless model since it will be almost as complicated as reality itself. Therefore, a group of actor[s] needs to be represented together (i.e. aggregated) as a single social entity in the models in most cases. There are two important issues that need to be considered in such representational decisions, such as actor aggregation, considering the specific context of transitions. The first issue is about the roles of the actors; independent of the detail level of the analysis, actors associated with different roles should be represented separately in the model. This is mainly due to the differences in the nature of these actors’ decisions, and the consequences of these decisions in the transition context. The second issue is about the preferences of the actors that determine their decisions; the preference structure of the actors, briefly, represents what they care about, and how much they care about these. Therefore, actor groups having significantly different preferences have the potential of diverging in their choices along the transition process. In that respect, it would be a better representation to treat these actor groups separately in a model.

Actors are mainly characterized by their role, extent of impact, preference structure, possessed information, and existing commitments in the model. The role of an actor is mentioned above. The impact of an actor indicates the relative scale of impact of an actor’s decisions/actions in the system. For example, a power generation company influences the system via investment decisions, and the investment fund available to a particular power company is representative of its impact in this particular system setting; the extent of impact a large energy company can make on the system is not the same with the one of a small energy company with limited investment power. Possessed information, as the term implies, indicates what is known to the actor in making choices. For example, a power company does not know the unannounced investment plans of the competitors, and the representative of this actor in the model should also be using information of similar scope and accuracy. Existing commitments are physical, economical, or intangible resources allocated to options in the past by the actor. Following the same example, the coal-based generation plants owned by the generation company constitute the company’s tangible commitment to coal-based thermal generation option. As a different example, a farmer’s past experience with pesticide-based practice (and resulting know-how) is an example of intangible commitments of the actor to a certain type of practice.

Preference structure, as mentioned earlier, represents what an actor cares about and how much it cares about these. Preference structure is a multi-dimensional construct, in which
each dimension corresponds to an issue relevant in the choices of the actors. One aspect of constructing a preference structure in the model is the choice of issues to be covered in this preference structure. Basically, an issue should be considered for being a part of the preference structure if any system actor finds the issue relevant and important in their choices with respect to available options. Considering the variety of actors in a socio-technical system, the list of issues may be expected to expand very quickly. However, generally a compact set of issues is predominantly used by the actors for choosing among available options in a specific transition context. Excluding the issues that are marginally important for major actor groups, and the issues of marginally small-sized actor groups in the system, it is possible to come up with a manageable set of key issues; i.e. 5-6 dimensions for the preference structure.

Once the dimensions of an actor’s preference structure are set, the next step is to quantify this preference structure. In order to be operational in a quantitative model, a preference structure should represent the importance of the issues for an actor in a quantitative way. Different implementations of quantified preference structures might be appropriate, but the simplest and the most intuitive one is to assign priority weights to these issues. Being meaningless quantities when considered in isolation, these weights provide information only about the relative importance of an issue compared to other issues. Measuring such weights directly is not possible, but they can be indirectly calibrated based on observations of the actors’ decisions under specific conditions.

e. How to formalize actors’ decision-making?

The actual reasoning procedures of individuals, or the decision-making processes in organizations are very difficult to identify, if possible at all in the first place. Therefore, the ambition in this stage is to develop decision formulations (heuristics) that generate outcomes that resemble the ones of actual actors in similar conditions. Such heuristics may as well be different from the actual decision-making processes of an actor, or an organization in detail or in some other sense. For example, people have a tendency to mimic people in their social networks in innovation adoption. It is not clear what is the actual cognitive process underlying such a behaviour. However, any decision heuristic that yields a modelled actor to have a higher tendency of adoption when the innovation is widely adopted in the actor’s social network can be considered as acceptable for modelling purposes.

Simply put, the actors in the model are facing a multi-objective decision process. The decision analysis field presents notable examples for formalizing such decision processes (Keeney and Gregory 2005; Keeney and Raiffa 1993). One key aspect of such formalizations is the preference structure, which has been discussed above. In the multi-objective decision setting, the preference structure of an actor represents the relative importance of each objective. Another key aspect is the attributes of options that are related to these objectives. Simply, it can be said that an actor monitors an attribute as an indicator for an option’s performance regarding a particular issue. For example, in the context of mobility, CO₂ emissions of a certain option may serve as the attribute monitored by an actor in relation to the minimizing environmental impact objective.

Specific implementations of the decision processes may vary, but in general they resemble each other: an actor assesses each option by combining the priority of each objective with the corresponding attribute of the option, which is related to the consequence of deciding
in favour of that option. Such an assessment can be summarized with a quantitative metric, which is a kind of overall score representing the degree of match between the option and the preferences of the actor. Such a metric is calculated according a *value function*. These values are used to compare alternative options, and constitute the basis of a decision for the actor. The decision can be continuous (e.g. which percentage of investment is allocated to coal-based plants?), as well as discrete (e.g. which type of car to buy?). In the continuous case, the score of the options, for example, may be directly proportional to the percentage of investment allocated to the options. In the discrete case, the scores may be used to select a ‘winner’ among alternatives, and purchase a certain type of car. Both the nature of the decisions, as well as the most appropriate formulation of the value functions should be decided on case-specific basis.

f. **How are the options characterized in the model?**

While discussing the actor-option framework, it was mentioned that the options are characterized by their embodied and disembodied attributes. Since it is not possible to represent the options in a model with their all attributes, a set of attributes relevant to the analysis context need to be selected.

Two attribute subsets are very important, and should be included in the characterization of the options in the model. The first subset consists of option attributes directly related to the decision making process of the actors. In other words, these are attributes an actor needs to know something about in order to assess the option. The range of electrical cars, the cost of electricity generation with wind turbines, etc. are typical examples of such attributes. The second set is related to the overall performance of the socio-technical system, especially related to the transition-characterizing aspects mentioned before. For example, the airborne pollutant emission from a waste management option is needed to calculate the total air pollution emission from the Dutch waste management system. The total pollution from the system is an important indicator of the environmental performance of the system as a whole, and pollution emission rates of each option are needed to evaluate such a system-wide outcome. Therefore characterization of the options should include this attribute, independent of whether actors use this information in their decisions, or not.

g. **Which mechanisms are ‘active’ in the analysis context?**

Not all mechanisms included in the actor-option framework are relevant in every analysis context. The set of mechanisms that is active in the specific analysis case needs to be identified. A mechanism can be considered as active if it can potentially lead to a change that is large enough to alter some actors’ behaviour within the time horizon of the analysis.

Despite differences among mechanisms, a set of common key points are needed to be specified for a mechanism that is considered to be active. Firstly, every mechanism has a trigger. This trigger can be like a discrete switch, or it can be more like an external pulse that determines the strength of the mechanism. For example, an actor’s investment resources can be considered as a latter sort of trigger for a resource-driven option development mechanism. Secondly, not all mechanisms operate at the same time-scale. Therefore, a pace needs to be specified for the mechanism. Thirdly, the consequences of a mechanism need to be specified, which is an intuitive requirement. One triggered, what is the specific aspect in the system a mechanisms changes? For an option development mechanism, this issue corresponds to specifying the particular option and its particular property being developed.
Some other points regarding the mechanisms are dependent on the type of mechanism considered. Therefore, the discussion on mechanisms will follow the mechanism categories discussed in the actor-option framework.

i. **Mechanisms related to option properties**

Options’ properties that are included in the characterization of the options are investigated individually at this stage. First of all, this investigation checks if a property should be treated as dynamic or static during the analysis. This decision mainly depends on the time scope of the analysis. Assume that the fuel efficiency of gasoline-based engines is very unlikely to develop in the following decade. In an analysis spanning a short time period that is proximate to a decade, this property can be treated as static; i.e. there are no active mechanisms to be covered in the model related to this aspect of the option.

For an option property that has the potential to change within the analysis’ time horizon, the next step is to postulate a set of mechanisms through which such a change takes place. For example, the purchase cost of electrical vehicles is expected to decline as a consequence of production increase expected in the future. Such an observation or assumption implies that a scale-driven change mechanism is influential on this property. Additionally, it also points towards the concept that drives the mechanism; i.e. scale of production (by provider actors). As a result, a scale-driven change mechanism that links some actors' behaviour (i.e. production scale) to a particular property of an option is established. Following such a procedure, the mechanisms assumed to be active are specified for the model.

ii. **Mechanisms related to actor perception**

The identification of the need for learning mechanisms is directly related to decoupling the actual information on the one hand, and what actors in the system know about it on the other. The actors act on information they possess (i.e. perceived information), rather than the perfect information about their surroundings. In most cases these two, i.e. actual and perceived information, differ to a certain extent. However, separate representation of every bit of information in the model as actual and perceived-by-the-actor is not always necessary.

It takes some time for an actor to learn about changes in a system that surrounds. This time gap can be referred to as ‘perception delay’ of an actor. Perception delays differ for different sorts of information: for example, it may take just weeks for users to learn about a new feature of an artefact (an option), but months or even years may elapse for the same actors to learn about an environmental problem. In cases, where the perception delay is considerably shorter than the regular pace of actor actions in the system (e.g. whether they alter their actions hourly, or yearly), the imperfections in the perceived information loses its significance in analyzing change dynamics. In the opposite case, perceived and actual information about a certain aspect of an option, or the system should explicitly be represented separately in the model (i.e. distinguishing the system as it is vs. the system according to the perceptions of the actor). In such cases, there should be some learning mechanism(s) that link what is happening in the system to what is perceived by the actor.

The specification of active learning mechanisms is based on determining the source of information and the pace of the learning process. The source can be actual (e.g. direct observation), other actors’ perception (e.g. learning about what is known to other actors),
or external sources (e.g. news, scientific/governmental reports). The pace of learning can be fixed as well as variable. In the fixed case, it is assumed that the actor is able to update what is known in a non-changing duration that is independent of contextual conditions. In the variable case, contextual conditions may speed up or slow down the learning pace. In individual learning mechanisms the intensity of direct observation can speed up learning (e.g. more experience with an option leading to faster learning about its attributes). In case of social learning, the number of information sources (e.g. more social neighbours communicating a new development) may yield a faster information flow, hence a shorter perception delay.

iii. Mechanisms related to actors' behavioural identity

Compared to the previous two groups of mechanisms, this group is much more challenging to identify and specify. This is mainly due to limited understanding and difficulty of empirically observing such concepts related to the internal decision processes of the actors. Despite this difficulty in representation, it is for certain that they play an important role in shaping transition dynamics. Therefore, even an intuitive and reasonable/justifiable representation is much more appropriate than ignoring these processes totally in an analysis.

In principle, the main steps of identifying and specifying these mechanisms are quite similar to what is discussed in the previous sections. The first issue is to come up with a set of assumptions regarding the nature of actor references, priorities and commitments; e.g. whether a decision reference will be treated as static, or dynamic during the time horizon of the analysis. In cases where the concept is assumed to have the potential of change within the time horizon of the study, the trigger (or the source) that drives the change of this concept needs to be specified. For example, assuming that environmental degradation may alter the priorities of an actor, environmental indicators such as water pollution and forest degradation can trigger change in the actor's priority for environmentally friendly choices and actions. In this case, such environmental dynamics act as the trigger for priority change for the actor in the model. The last stage of the specification process is related to the pace of change. Once a trigger event/process takes place in the system, how fast do the actors respond to this and alter their behavioural identity? The answer to questions of this type completes the picture in specifying the mechanisms.

7.3. Conclusions

This chapter presented a set of guidelines that explains the process of developing models based on the conceptual perspective of the actor-option framework. The process of model development is organized according to a sequence of seven fundamental questions related to the identification of the system boundaries, as well as the internal representation of the socio-technical system being studies.

As mentioned, the seven questions introduced in the chapter provide some structure to the model development process. However, these questions are proposed as assistance rather than obligation. It may be possible to develop models based on the actor-option framework via following different approaches. The set of questions compiled in this chapter simply reflect the way we develop and use models in the context of this study.

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2 The term ‘neighbour’ is not used to refer to spatial neighbourhood, but to the set of actors with whom a certain actor interacts in some sense.
Although the questions are meant to be used while developing simulation models, they can also prove useful just for structuring qualitative analyses and discussion. Answering these questions with regard to a specific case can be enough for developing qualitative conceptual models for analysis and discussion, if that is the ultimate objective. However, in order to develop a quantitative simulation models further specification of the basic concepts and relationships is needed. Although the chapter also provides some hints on ways of specifying the models to be developed, we do not prescribe a particular way to do it. While discussing the models developed for this study in Chapters 8 through 10, we provide some examples of particular ways of specifying such models.
Transition in the Dutch Waste Management System

The transformation of the waste management system in the Netherlands is an example of a recently completed transitional change. Starting from late the 1960s, the waste management system underwent a significant change, which involved changes in the environmental impact, infrastructure, regulations, and public attitude in a time horizon of approximately 30 years. The dominant waste management practice of landfilling in the 1970s, has become the least preferred option over the years. The multi-dimensional nature of such a change (e.g. initiating regulations, triggering investment in alternative options, formation of public support, increasing soil pollution) made the case an interesting one in the transition field (Loorbach 2007; Raven 2007). A brief summary of the 30-year transition is given below.

8.1. Overview of the transition process

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 an 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 management of waste (i.e. collection, treatment, and disposal). An almost exponential growth of the waste to be handled had been 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 the 1970s 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 the public opinion. The law on waste was pronounced and a method for ranking different waste management practices—better known as the “Lansink’s Ladder”—was made public. The introduction of the

1 Some parts of this chapter are reproduced from Yücel and Chiong Meza (2008), and Yücel and van Daalen (2008b).
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 services.

In the 1980s an increase in the environmental awareness has been observed mainly due to the deforestation and acid rain issues gaining publicity. Additionally, 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 triggered further 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 management of waste. 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 generation.

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 an equilibrium, and were stable.

8.2. Model description

While introducing the model developed for the Dutch waste management case, i.e. WasteTrans, the discussion follows the questions introduced in the previous chapter in order to reveal the practical utilization of these questions in developing models.

a. What is the societal function/need of concern?
The societal function that characterizes this case is the management of waste, which corresponds to the collection, treatment and disposal of waste. The spatial scope of the transition is the Netherlands, and the time horizon of the transitional change is an approximately 30-year period from the late 1960s until the 2000s.

b. Which aspects of the societal function characterize the transitional change?
The transitional change in focus in this case is mainly about the environmental impact (e.g. air and soil pollution caused) of the overall waste management system. The environmental impact is closely related to the amount of waste that needs to be disposed, and the ways this waste is disposed. Therefore, the share of the different waste management alternatives can also be seen as a transition-characterizing aspect in this case.

c. What are the alternative means of fulfilling the societal function?
There are three major ways of waste management that dominate the Dutch waste management arena. These three means of managing the waste constitute the options included in the model; namely landfilling, incineration, and re-use/re-cycling².

2 Abbreviations used for the options in the model description and the model outputs are as follows; ‘land’ for landfilling, ‘inc’ for incineration, and ‘reuse’ for re-use/recycling.
d. Who are the major social actors in the system?

Considering this function, as well as the historical accounts about the change process, it is seen that all actor roles are relevant for the way transitional change unfolded in this case. The actors of the system, and the roles they are associated are as follows:

i. Users/Practitioners

Local municipalities, being responsible for managing the waste (i.e. collection, and then removal of the collected waste), are identified as the group of actors that utilize existing options for waste management. In other words, they constitute the user/practitioner actors in the model. The key decisions of these actors are about allocation of the generated waste among the available waste management options. Based on their assessment about the available options, they alter the share of each option in their waste management portfolio.

ii. Providers

Contractors who provide waste management services (e.g. incineration plants, landfilling sites) to the municipalities. Being responsible for maintaining the waste management options, the key decisions of the providers are related to capacity investment: they decide on how much to change their investment behaviour in terms of changing the percentage of capital investments allocated to the options.

iii. Regulators

Central government is identified as the regulator in this case, since it intervenes with the waste management system through measures like subsidies, taxes, and emission regulations. Such interventions can be in numerous forms. A representation at a detail level that covers all these forms is evaluated not to be necessary. As a result, the intervention of the regulator favouring or opposing a certain option is represented with the concept of ‘regulatory support’ in the model. At each time interval, the regulator decides on how much to alter its regulatory support for the available options.

iv. Opinion groups

The role of public opinion seems to be influential, especially, in shaping the regulator’s, and practitioners’ decisions in the context of waste management. Therefore, their explicit inclusion in the model is important. The impact of this group on other actors is through the state of their opinion (e.g. supporting or against) regarding the means of waste management. This opinion is conceptualized to change as a consequence of periodic assessment of the available options and the state of the waste system, in general.

Studying the historical accounts of the developments in the Dutch waste management system, it is concluded that inter-role interactions play a major role, while intra-role variety and interactions do not appear as an important driver of change processes. Additionally, variations within each actor role do not seem to be very significant. Based on these observations, the aggregation level of the representation is kept high, and the actors of a particular role are aggregated into a single collective actor in the model. In summary, one collective actor is used in the model to represent each actor-role.

3 Abbreviations used for the actors in the model description, and the model outputs are as follows; ‘reg’ for the regulators, ‘pract’ for the practitioners, ‘prov’ for the providers, and ‘sup’ for the opinion groups/supporters.
Different actors have different preference structures since the relevant objectives/issues differ for each actor-type in the given context. Table 8.1 summarizes the objectives of each actor-type, which constitute the dimensions of the actors’ preference structures. Additionally, the table also includes the option attributes that are used by the actors in evaluating the options with respect to each objective. As can be seen from the table, the coverage of the preference structures are not confined to techno-physical aspects of the options, but also cover aspects related to other actors’ behaviour such as regulatory support, or public opinion. It is important to note that the preference structures comprise the issues that have the potential to cause significant changes in the way actors decide during the transition period. Therefore, some issues that naturally play a role in the actor’s decisions are not considered, if there is no significant change in the relative situation (i.e. relative advantage with respect to other options) of the available options related to these issues. For example, practitioners are naturally expected to take costs into account. However, the case studies that have been used as the basis of this modelling exercise do not report any significant change in the relative cost advantage of one option to another in the course of this transition. Therefore, minimization of operating costs is not included in the preference structure of the practitioners.

Table 8.1. Objectives in the preference structures of the actors, and related option attributes

<table>
<thead>
<tr>
<th>Government (Regulator)</th>
<th>Max. compliance with public opinion</th>
<th>Public support for the options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. soil pollution impact</td>
<td>Soil pollutants caused by the options</td>
<td></td>
</tr>
<tr>
<td>Min. air pollution impact</td>
<td>Air pollutants caused by the options</td>
<td></td>
</tr>
<tr>
<td>Min. space used</td>
<td>Space required per waste processing capacity</td>
<td></td>
</tr>
<tr>
<td>Local Municipalities (User/Practitioner)</td>
<td>Max. compliance with public opinion</td>
<td>Public support for the options</td>
</tr>
<tr>
<td>Min. soil pollution impact</td>
<td>Soil pollutants caused by the options</td>
<td></td>
</tr>
<tr>
<td>Min. air pollution impact</td>
<td>Air pollutants caused by the options</td>
<td></td>
</tr>
<tr>
<td>Min. space used</td>
<td>Space required per waste processing capacity</td>
<td></td>
</tr>
<tr>
<td>Max. compliance with regulations</td>
<td>Regulator support for the options</td>
<td></td>
</tr>
<tr>
<td>Waste Contractors (Providers)</td>
<td>Max. compliance with regulations</td>
<td>Regulator support for the options</td>
</tr>
<tr>
<td>Max. profit</td>
<td>Supply gap in options' capacity</td>
<td></td>
</tr>
<tr>
<td>Public/NGOs (Opinion Group)</td>
<td>Min. soil pollution impact</td>
<td>Soil pollutants caused by the options</td>
</tr>
<tr>
<td>Min. air pollution impact</td>
<td>Air pollutants caused by the options</td>
<td></td>
</tr>
<tr>
<td>Min. space used</td>
<td>Space required per waste processing capacity</td>
<td></td>
</tr>
</tbody>
</table>

1 Amount of soil pollutants released as a result of processing a certain amount of waste using an option
2 Amount of airborne pollutants emitted as a result of processing a certain amount of waste using an option

e. How to formalize actors’ decision-making?
As mentioned earlier, a key aspect of the decision formulation is a value function to be used by the actors to evaluate each option. A relatively simple value function is used in this modelling study. Let \( d \) represent a particular decision for the actor (e.g. a unit increase in the percentage of waste incinerated), and \( x_{di} \) represents consequences of making the decision \( d \) related to the \( i \)th objective in the actor's preference structure (e.g. air pollution caused). Then, the actor is assumed to value the consequences of the decision \( d \) as follows;

\[
V_d(t) = \sum_i \lambda_i(t) \nu(x_{di})
\]  

[8.1]
In Equation 8.1, $v(\cdot)$ is the *component value function* (Keeney and Raiffa 1993). These functions are used to evaluate the consequences of decisions for each objective/issue in an isolated manner, and the decision that yields the best possible consequence with respect to that particular objective yields a value of 1 (i.e. $v(x_{best}) = 1$). All decisions are evaluated in a range of $[0,1]$ according to these component value functions. $\lambda_i$'s in the formulation represent the weight of the objective $i$ in the preference structure of the actor. In some sense, they are the priorities of different objectives for the actors.

The time index in the value function implies that the actor may value the same decision differently at different times. This is mainly caused by the dynamic nature of the priorities. The preference structures of the actors are not assumed to be static in the model, but they change over time through changes in $\lambda_i$'s. Such a change may yield an actor to value a decision very differently over time.

The outcomes of the value functions are used to change the decisions of the actor. For example, in the case of waste contractors the instantaneous decisions are assumed to be about the percentage of new capital investment allocated to the options. In the model, the changes in such decisions are formulated by using bidirectional change equations. An example of such equations is given below, which represents the rate of change in the investment percentage for landfilling (i.e. $I_{land}(t)$);

$$\frac{dI_{land}(t)}{dt} = s_{reuse,land}(t) + s_{inc,land}(t) - s_{land,reuse}(t) - s_{land,inc}(t)$$ [8.2]

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

$$s_{i,j}(t) = H(V_i(t) - V_j(t))[\alpha(V_i(t) - V_j(t))I_i]$$ [8.3]

where $H(.)$ is the Heaviside function (i.e. $H(x)=1$ for $x>0$, and $H(x)=0$ otherwise), $V_i$ is the value attributed to option $i$, and $\alpha$ is a constant representing the normal pace of fractional change. For example, when an actor attributes a higher value to choosing landfilling compared to incineration (i.e. $V_{land} > V_{inc}$), $s_{inc,land}$ is positive, whereas $s_{land,inc}$ is zero due to the Heaviside function. As a result of such a valuation, there will be shift of investment percentages: the investment share of the incineration option will decrease, and this will shift to the landfilling option and increase its investment share.

Similar formulations are used for all actor types. The only customization in the equations that differentiates the responses of the actors are $\lambda_i$'s that represent priorities of the actors, and $\alpha_i$'s that determine the possible pace of decision change.

One important aspect of the used formulation is related to the status quo seeking nature of the actor. If two available options are evaluated to be proximate in desirability, no significant change takes place in the decisions of the actors. This implies that in order to trigger a significant change, an alternative option has to outperform the current favourite option of the actor.

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4 Considering the aggregate nature of the actors in the model, their decisions are not discrete, as choosing whether to use landfilling, or not. The modeled decisions are more like resource allocation decisions (e.g. what percentage of available investments will be made for incineration capacity development?), and are continuous in nature.
f. **How are the options characterized in the model?**
Considering the issues in the preference structures of the actors, it suffices to characterize the waste management options in terms of three techno-physical attributes; *airborne pollutant emission*, *soil pollutant release*, and *physical space needed for waste processing capacity*. Apart from these, *regulatory* and *public support* for an option are also considered as aspects related to the option characterization. Since they are related to the social embedding rather than techno-physical nature of the options, the latter two aspects are disembodied type of properties of the options. Finally, the *demand-capacity balance* is another aspect relevant for the provider actors. It is assumed that this balance acts as an indicator of the profitability of the options.

g. **Which mechanisms are ‘active’ in the analysis context?**

i. **Mechanisms related to option properties**
Both incineration and landfilling are based on mature technology and practices. In that respect, experience-driven change is assumed to be negligible for the techno-physical attributes of the options in this context. Similarly, none of these attributes are influenced by the scale of use in a significant way; i.e. no scale-driven change for techno-physical attributes. The major change processes that act on the three techno-physical properties are *resource-driven* and *exogenous change* mechanisms. Exogenous change happens through technological developments and spillovers, and is not influenced by the internal dynamics of the waste management system. However, the exogenous change only influences the technological possibilities that can be used in the Dutch system, but not the performance of the existing techno-physical structure of the system. This means, for example, despite cleaner incineration furnaces being available, the Dutch incinerators still utilize less clean ones. Operationalization of such technological possibilities happens through a resource-driven change mechanism. According to this mechanism, the investments of the providers drive improvement in the attributes of the utilized options. The pace of development is dependent on three aspects; room for development, scale of investments, and pressure for improvement. The *room for development* corresponds to the gap between the best feasible and the current levels of an attribute. The *pressure for improvement* is exerted by the regulator, and the regulator’s priority for an issue signals such a pressure in that direction (e.g. increasing priority of air pollution issue implies a pressure for improving the airborne pollutant emission attributes of the options). In summary, the pace of attribute change is a conjoint outcome of the choices of two different actor groups in the system; the regulator and the providers.

The *demand-capacity balance* is about the provision system that surrounds an option, and qualifies as a disembodied property. The relevance of the attribute comes from the fact that it plays a role in shaping the investment decisions of the provider. This attribute is altered by two mechanisms. The processing capacity is clearly dependent on the investment made for a particular option. In that respect, it is subject to resource-driven change; the provider investments (i.e. resources) allocated to an option determine the expansion of the corresponding processing capacity. The demand is dependent on the scale of waste allocated to a certain option. In other words, it changes through a *scale-driven change* mechanism. As a result, the demand-capacity balance changes as a combined outcome of two simultaneously active and independent mechanisms.
**Mechanisms related to actor perception**

Considering the actors in the model, individual learning does not seem to be relevant. Social learning can be assumed to play a role in the diffusion of new information (e.g. total airborne pollution caused by incineration in a year) within the opinion group. The most relevant learning process for all actor types seems to be the learning from external sources. Regarding the techno-physical attributes of the options, technical reports and specification documents serve as the exogenous information sources. For other attributes, as well as performance of the system as a whole (e.g. total space needed for landfilling), scientific as well as news reports serve as the source. Considering these, it is assumed that the actors learn about new information with a perception delay. The pace of learning depends on this delay, as well as on the difference between the perceived and the actual information; i.e. the less the error in perceived information is, the less the correction that will take place via learning. The aforementioned learning process is represented via an information smoothing formulation widely used in system dynamics and feedback modelling practices (Sterman 2000);

\[
\frac{d\hat{x}_{i,j}(t)}{dt} = \frac{x_i(t) - \hat{x}_{i,j}(t - dt)}{pd_j}
\]

where \(\hat{x}_{i,j}\) is the level of attribute i perceived by the actor j, \(x_i\) is the actual level of the attribute, and \(pd_j\) is the perception delay of the actor j. The perceived information is updated according to this equation in each time interval for the actors.

**Mechanisms related to actor identity**

All actors, except the providers\(^6\), are assumed to have dynamic preference structures, which change as a response to endogenous developments in the system. All the actors use the initial state of the system in terms of air and soil pollution as the reference point. As the pollution increases (i.e. trigger development), this yields an increase in the corresponding priority of an actor. According to the way it is conceptualized, for example, if an actor realizes that the soil pollution has reached levels of four times what it used to be, the actor becomes more sensitive to the soil pollution performance of the options in its choices. Since the preference structure indicates the relative importance of different issues, a certain issue gaining priority indirectly means others losing importance in the option assessments of the actor.

Another aspect of the actors’ identity is the references used in the option assessment; i.e. what is a good airborne pollutant emission performance? This is also dynamic in the model. It is assumed that the actors use the information on ‘what can be achieved technologically’ as the basis of comparison. In other words, the best performance available (in airborne pollutant emission, soil pollutant release, or space occupancy) serves as the basis of evaluation. Each option is assessed with respect to an attribute based on where it stands compared to the best attribute level known among all options. Therefore, an option going through rapid technological improvements may also influence the actors’ assessment of the other options in a negative way.

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5 This formulation is equivalent to the exponential smoothing used in forecasting applications

6 None of the issues covered in the preference structure of the provider has the nature of getting more/less important as a consequence of the developments related to the waste management system. They may change due to developments such as economic crisis (e.g. profit becoming more important), but then this should be introduced as a scenario, and not covered as an endogenous dynamics in the model.
Further details about the *WasteTrans* model, which include the parameter values and a detailed discussion on equation formulations, can be found in Appendix A.

Following the model development steps described before, the model for analyzing the dynamics of the Dutch waste management transition has been developed. However, the linear process of development does not reveal much about the internal complexity of the developed model; no feedbacks, or actor interactions are explicitly introduced into the model. Actually, the conceptual elements, and the mechanisms identified and formulated one by one constitute the pieces of such a complex structure. When the model structure is complete, it is possible to spot aspects that create dynamic complexity such as feedbacks and interactions among actors’ choices. Figure 8.1 presents an example of how individual mechanisms interlock to form feedback loops that involve different actors. The figure simply depicts a sample set of feedback loops that influence the development of the incineration option. The arrows indicate relationships and/or processes that link two aspects, and they mostly correspond to individual mechanisms mentioned above.

![Figure 8.1. An illustrative example of how mechanisms form feedback loops in the system](image)

### 8.3. Sample simulations and analysis

The model aims to generate change dynamics in the utilization of different waste management practices, and the changes in overall environmental impact that result as a direct consequence of that. Besides replicating the historical dynamics, the model-supported analysis also focuses on linking the observed dynamics to underlying mechanisms that drive such dynamics.

#### a. Base run

The case study that is used as the basis for this modelling exercise (i.e. Loorbach 2007) provides qualitative descriptions for the various changes observed in the waste management context during this transition period. However, there are few quantitative data about the observed dynamics. One of these few empirical data series is about the amount of waste (and percentage
of total waste) managed through different practices. Unfortunately, this empirical data goes back only to 1985. When the model-generated behaviour is compared with this historical data series (Figure 8.2), it is concluded that the model is successful in replicating the historical trends. Although there are some numerical deviations, the model output is evaluated to be satisfactory considering that the main goal of the analysis is to achieve a pattern-wise fit rather than a point-wise numerical fit.

30-year developments with respect to the previously identified transition-characterizing aspects of the waste management system are given in Figure 8.3 and Figure 8.4, which are in accordance with the qualitative accounts in the historical case study. As can be seen from Figure 8.3, the roles of the different practices in the system change significantly over the time horizon of the analysis. Figure 8.4 presents the overall environmental impact of the system.

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**Figure 8.2.** Comparison of the model output for waste allocation percentages with the actual data.

**Figure 8.3.** Percentage of waste allocated to the available options by the municipalities.

7 The reader may refer to Yücel and Barlas (In Press) for a comprehensive discussion on the difference between these two perspectives in evaluating model output with respect to a reference empirical data.
changes in the plot should be evaluated based on the fact that the total waste being managed during this 30-year period is increasing. If the system would have continued to function as it did in 1970s, the environmental impact indicators would be increasing exponentially. In that respect, it is possible to talk about a transition in the dynamics of the environmental impact of the system from a strong growth to a stabilized behaviour.

Linking the observed system behaviour to changes at the actor level is very important in understanding the transition process; how do mechanisms interact and yield these overall system-level consequences? In order to understand the change in the municipalities’ behaviour, two issues are relevant to investigate. The first issue is the changes in the preference
structures of these actors (Figure 8.5). The overall environmental impact of the system triggers important changes there; first, the soil pollution becomes the biggest concern, and later the air pollution gains significant importance. The latter development, for example, is triggered by the rapid increase in the overall air pollution emissions in the 1980s (Figure 8.4), which is a consequence of the internal dynamics related to the incineration of more waste. An important observation is the time lag between the dynamics of the environmental impact, and the priority changes triggered by these dynamics. The time it takes the actors to perceive the extent of the problem (i.e. learning mechanisms), and the slow pace in altering the priorities (i.e. preference change mechanism), which might be attributed to institutional inertia for example, are mainly responsible for this time lag. In short, the actor-related mechanisms seem to be mainly responsible for decoupling the cause (i.e. worsening environmental impact) and the effect (i.e. change in the waste management practices) in time, which is a very important issue in explaining the change dynamics in the system.

The second issue that is important for understanding the behavioural changes of the municipalities during the transition process is the role of the other actors’ behaviours. The municipalities are assumed to comply with the central government (i.e. the regulator actor) on waste management issues. Therefore, the changes in the way regulatory support for different practices changes plays an important role in steering the transition process. The priorities of the regulator, and the resulting dynamics of the regulatory support for the waste management practices are given in Figure 8.6 and Figure 8.7, respectively.

In analyzing the changes in the regulatory support, and how it is related to the overall changes in the system, a simplified causal-loop diagram (CLD) is used to discuss the interaction of several feedback loops that shape these changes. The diagram shows five feedback loops that are simultaneously active and interacting. The loops are numbered from 1 to 5, and each link is labelled with the number/s of the loop/s it belongs to in order to facilitate the understanding of the diagram.
Figure 8.7. Regulatory support for the waste management practices

Figure 8.8. A Simplified CLD of the feedback mechanism underlying the regulator's behaviour
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 the total waste to be handled, the growth in the soil pollution exceeds the levels that can be suppressed via the degradation mechanism. The observed increase in the soil pollution triggers L2, the second balancing loop in the diagram. According to this loop, the regulator changes its priorities with a time delay following the recognition of the increase in the soil pollution. The actor, therefore, changes its assessment of the options, and the incineration option becomes more favourable. This induces further changes for the other actors. For example, as a consequence of the changing regulatory support for the incineration option, this option becomes more favourable for the waste contractors (i.e. providers) and a shift in the investments towards incineration facilities starts (see Figure 8.9). The municipalities also react similarly, as discussed before. Via these mechanisms the percentage of waste being 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 is that L2 would 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, and these balance the shift to the incineration option 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 practice to keep itself as a favourable 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 already illustrates adequately the interplay between the landfilling and the incineration options in the regulatory arena.

b. Sensitivity analysis

The model that is developed for this case includes some ‘soft variables’, which are difficult to quantify due to them being incommensurable. For example, the actors’ priorities for different objectives are such hard-to-quantify concepts, but at the same time they are too important to be ignored. These priorities can easily be ranked based on the qualitative discussions in the historical case study, but there are several alternative ways of quantifying these variables that would be consistent with a particular ranking of them. This kind of problems makes it crucial to investigate the robustness of the results; are the system behaviour and its causes still the same when these soft variables are initialized differently? It is crucial, for the sake of evaluating the robustness of the conclusions, to ask this type of questions related to the model variables that have loose empirical grounding.

Accordingly, a comprehensive set of sensitivity tests have been conducted in order to investigate the robustness of the previously discussed insights regarding the waste management transition. For instance, in one of the tests the initial values for the actor priorities are initialized differently while preserving the ordinal rankings. 1000 such different initial priority values are used to simulate the system, and the resultant system behaviours are investigated. Figures 8.10 and 8.11 present the results from this experiment with the initial values of priorities.
As can be seen from the plots, the overall behaviour patterns regarding the percentage of waste managed through incineration and landfilling are the same, with some changes in the numeric values. Further sensitivity tests have been conducted using the same approach for other model variables, and the results of these experiments are given in Appendix A.

Based on the results obtained during sensitivity analyses, it can be concluded that, despite sensitivity in the numerical results, the pattern-wise sensitivity of the model is low. This indicates that the observed long-term behaviour is strongly conditioned by the feedback structure modelled, rather than some individual variable values or randomness. Therefore, the insights discussed in the previous section are still valid even if the soft variables in the model are initialized in different ways.

8.4. Conclusions from the modelling study

The case study on the transitional change of the Dutch waste management system served as a testing ground for the proposed conceptual framework, and the simulation-supported analysis approach. In conducting the modelling study, we aim to demonstrate an application of the framework, and the ways the developed model can be used. Besides such a demonstrative purpose, we also investigate the potential limitations of the framework during this hands-on experience.

An important question was about the extent to which the general framework could be used to represent the case-specific developments and conditions: could we tell the key points of the waste management story in terms of the options, actors, and mechanisms? As a result of the conducted investigation, it is concluded that the conceptual framework is rich enough in basic elements and mechanisms to represent the prominent developments in the waste management transition case, such as the changing perspectives about the waste management practices, improvements in incineration technologies, and the regulatory changes on pollutant emissions.
The aforementioned question also helped us to identify some limitations of the framework. One of the encountered conceptual limitations is about representing the formal institutions and the mechanisms through which they change. Different from techno-physical, and social aspects that are related to decision-making, the framework does not specify the way formal institutions and their change processes can be incorporated into the models. In this model, an abstract proxy variable (i.e. regulatory support), which represents the state of the regulations and formal institutions favouring a particular option, is used to incorporate dynamics of formal institutions into the model. Despite saying very little about the specific regulations, the implementation served our purpose well in representing the direction of change in the regulatory arena.

A practical limitation that poses difficulty in translating the conceptual models into quantitative simulation models is related to the quantification of the soft variables, such as the preferences of the actors. Although the case study provides information about the relative importance of different issues, it is possible to quantify the preferences in numerous ways that are consistent with the given qualitative information. This brings in the need for extra caution in interpreting the model output, and in jumping to conclusions. One way of addressing this limitation is testing the robustness of the conclusions under different quantifications. The sensitivity analyses presented in the previous section is a methodological approach to conducting tests for this purpose, and to build up confidence in the robustness of the drawn conclusions.

The developed model, i.e. WasteTrans, is successful in replicating the historical development trajectories of the key system variables, such as the amount of waste allocated to different waste management streams. Since the model builds on the historical accounts discussed in the case study, this constitutes evidence supporting the consistency and sufficiency of the transition story given in the case study. The developments and issues that are discussed in the case study are consistent in the sense that they can be incorporated in a formalized simulation model. Additionally, the developments claimed to be responsible for the transition in the case study constitute a sufficient explanation, since the corresponding simulation model is able to generate (replicate) the historical dynamics of the system. If we consider the case study as a hypothesis about the key processes that drive the historical transition, the model serves the purpose of putting this hypothesis to the test and providing the opportunity to improve it by pointing out inconsistencies, or generative insufficiencies. In that respect, the way we use the WasteTrans model can be considered as an example of the using models for theory testing and development, which is discussed in Section 2.3.

The model also serves the purpose of developing general conclusions and insights regarding the way the transition process unfolded. First of all, the model structure constitutes a generative explanation for the observed dynamics: it is a coherent whole of processes that replicates the evolution of the system during the transition process. In a way, it connects the dots along the transition trajectory by explaining how the system changes from a certain state to the next one in the course of the transition. As a result, it is possible to investigate and to reason about the transition dynamics based on this structure, as we did in our discussion regarding the shift in the regulatory support using a causal-loop diagram.

This type of reasoning based on the model structure leads to some general insights about the
transition dynamics. Before doing so, it is important to highlight some aspects of the developed model, which allows us to make the observation to follow. The model integrates the two sides of a socio-technical transition via covering changes in the actor perceptions and value structures (i.e. changes in the social aspects), and the changes in the infrastructure and technology (i.e. changes in the techno-physical aspects). Additionally, the model incorporates the feedback between the functioning of the system and its environment: it closes the feedback between the aggregate consequences of the system's mode of functioning (e.g. pollution caused), and the internal dynamics of the system (e.g. actors' waste-related behaviour). Changes in the system's environment are generally treated as exogenous developments in most qualitative analysis and also in modelling studies, rather than as endogenous as has been done in this case.

The endogenous representation of the system's environmental impact, and closing the loop between this impact and the preferences of the actors is crucial in explaining the developments in this case. This social control loop is the main driver in slowing down and stopping the empowerment of the incineration option in the system. Two key aspects are important for such a loop; an unwanted consequence of using a particular option, and observability of the consequence. The latter requires the consequences to be observable in the local context of the actors, and with a short time delay. Then the control loop acts as a very important driver against a particular option, as in the case of incineration (e.g. local air pollution as immediately observable and unwanted consequence). A similar control loop also exists for the landfilling option, but the unwanted consequences (e.g. groundwater pollution) of landfilling were observed with a considerably longer delay. Therefore, the move against the landfilling practice started long after the option dominated the system prior to the considered transition period. Establishing such social control loops can be an effective safety mechanism for the systems in transition against the empowerment of undesirable options, in general.

In the analysis, it is observed that the system demonstrates inertia against steering away first from the landfilling option, and later from the incineration option. One of the sources of such inertia is observed to be the delay in the perception of the environmental consequences of the waste management practices, and the time it takes for the actors to change their preference structures based on this information. More importantly, the change in the system propagates along the actor types: the regulator is the first to alter its behaviour, and then this influences the way municipalities behave, and then this in turn translates into changes in the capacity investments of the waste management companies. The actor types that recognize the problem and the need for change (i.e. opinion groups and the regulator), and the actor types that have a direct influence on the system's functioning are different (i.e. the providers and practitioners). This inter-role propagation of the change also acts as a very important source of the inertia in the system after the unwanted consequences of a particular practice becomes apparent.

Closely related to the issue discussed above, the model also shows how an inferior option may obtain and sustain a significant place in the system as a consequence of interacting technological development and information flow processes. The incineration practice reaches a significant share until its 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 processes 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.
Transition in the British Naval Transportation System

The second historical case that is modelled using the *actor-option framework* is the transition from the sail-ships to the steam-ships in the British naval transportation system, which is discussed in detail by Geels (2002a). Based on the documented quantitative data and qualitative descriptions of the change process, a simulation model, i.e. *NavalTrans*, is developed, and the model has been used to analyze transition dynamic through simulation experiments.

9.1. Overview of the transition process

In this section, a brief summary of the selected socio-technical transition case will be given. A more comprehensive overall discussion of this historical case with a transition perspective can be found in (Geels 2002a). Apart from that, more specific information on the process and the technologies can be found in other supplementary publications (e.g. Craig 1980; Fletcher 1910; Harley 1988; Lambert 1999). As mentioned before, the selected historical transition takes place in the British naval transportation system. As a result of this transition, the dominance in the naval transportation shifted to steam-powered ships from the formerly dominant option of the sail-ships.

The beginning of the transition period can be characterized by the clear dominance of the sail-ships, and related economic and social practices in the transportation of goods, passengers and mail to overseas. Despite already being in use during those times, the utilization of the steam-ships was limited mainly to transportation on inland waterways, due to shortcomings in range, operating cost and performance in open seas.

Three main markets existed for these ‘competing’ transportation options; merchandise, passengers and mail. Being independent of wind availability, the steam-ships were much

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1 Some parts of the chapter are reproduced from Yücel and van Daalen (2008a; 2008c).
2 Three different models with differing levels of actor aggregation are constructed for this transition case, which are all based on the *actor-option framework*. A comparative analysis of these three models is reported in detail elsewhere (Yücel and van Daalen 2008c). Considering the objectives of this chapter, only the one with the least actor aggregation is discussed here.
more reliable in terms of travel times, and also they were faster on average. With those characteristics, they were quite suitable for the mail and the luxury passenger markets. However, their technical shortcomings related to range (due to coal supply) and operating costs were balancing the advantages, and probably preventing the further utilization of the steam-ships apart from the inland water transportation market. Especially range was a significant problem for long-distance merchandise to/from North America and India.

Due to an increasing demand for regular and fast mail services, the steam-ships started to diffuse this market segment, mainly induced by the subsidies provided by the government for mail transportation with the steam-ships. Parallel to this, significant technological developments were realized in the steam-engine technology. These were partially due to the exogenous developments attained in other fields where steam engines were used. Additionally, a wider utilization of the steam-ships also resulted in some gradual improvements. Especially the construction of refuelling stations, and the improvements in the fuel efficiency made the steam-ships a viable option even for the long-range transportation. These developments during the transition period put the steam-ships at a strong competitor position against the sail-ships.

Towards the end of the transition period, the steam-ships were evaluated to be superior to the sail-ships in most of the aforementioned market segments. Despite this fact, the sail-ships were still in use, especially in the more cost sensitive segments such as low value freight transportation. To summarize the change in figures, the British naval transportation market in which 95% of the vessels (in terms of tonnage) were sail-ships around 1850s, transformed into a steam-ship-dominated state by 1910. At the terminal point, only 5% of the total vessel capacity consisted of sail-ships.

9.2. Model description

The description of the model developed for the naval transportation case follows the structure that is introduced in Chapter 7, and is organized according to the previously introduced guiding questions.

a. What is the societal function/need of concern?
The function of concern is the naval transportation of goods, passengers and also mail in Great Britain. The analysis focuses on an approximately one hundred-year period from the late 1800s until the early 1900s.

b. Which aspects of the societal function characterize the transitional change?
The main aspect that is of concern in the analysis is the power source used in transportation; i.e. wind or steam. Although it is a single technological aspect to evaluate the extent of transition, a change in this aspect actually implies significant changes in the system such as changes in the inventory of ships, fuelling services, ship construction and maintenance sectors.

c. What are the alternative means of fulfilling the societal function?
Considering the societal function as well as the transition-characterizing aspect of the study, two options are identified as distinct alternatives; steam-ship-based transportation and sail-ship-based transportation.

3 Abbreviations used for the options in model description and model outputs are as follows; ‘sail’ for sail-ship-based transportation, and ‘steam’ for steam-ship-based transportation.
d. Who are the major social actors in the system?

Social actors to be represented in the model are investigated by going through the previously introduced actor roles, and considering the social actors that occupy these roles in the naval transportation system.

i. Users/Practitioners:

Naval transportation serves various markets, such as freight transportation, passenger transportation and long-distance mail. In that respect, there are different actor groups who utilize the naval transportation options with differing needs. Merchants, passengers and government (as the operator of postal services) are three such social actor groups. Furthermore, it is misleading to assume that all merchants are similar: depending on the nature of the freight their priorities and objectives differ significantly. This also holds for passengers. Therefore, these two social actor groups are further disaggregated into sub-groups. As a result, seven major actor groups, which are all subgroups of the practitioner type of actors, are evaluated to be relevant for the case, and represented separately in the model. These actor groups, as well the relative importance of different issues for these actor groups are presented in Table 9.1.

Table 9.1. Practitioner groups and their priorities

<table>
<thead>
<tr>
<th>Type</th>
<th>Consistency in travel times</th>
<th>Speed</th>
<th>Cost</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merchant - Type I</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>(Long distance, Low value freight)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merchant - Type II</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>(Long distance, High value freight)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merchant - Type III</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>(Short distance, Low value freight)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merchant - Type IV</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>(Short distance, High value freight)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Government Postal Service</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Luxury Passengers</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Emigrants</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Although all these actor groups are on the demand-side of the naval transportation system, the nature of their demand, and hence the type of decisions they make are slightly different. The aggregate consequence of the merchant groups’ decisions determines the amount of freight to be shipped with the available transportation options in a time period. Postal services’ assessment of the available options, and the following decisions determines the amount of delivery to be shipped via a certain option. Finally, the passengers’ decisions determine the share of the each option in the passenger market, or more specifically the number of passengers using a particular type of ship for their travel needs.

ii. Providers

The actors responsible for the provision of the vessel capacity and the infrastructure are also not homogenous. Two sub-groups are identified; individual ship owners and large shipping
companies. These two actor groups, and their priorities are given in Table 9.2. As can be seen, the major difference between these two provider groups is their sensitivity to high investment costs mainly due to the individual owners’ limited access to investment funds and vulnerability. Additionally, they also differ with respect to the capital investment resources they control.

As a direct consequence of having the providers responsible for the capacity provision (e.g. the number and the tonnage of ships of a particular type), the providers are conceptualized as being in control of capital investment resources, and they allocate these resources among the available options.

Table 9.2. Provider groups and their priorities

<table>
<thead>
<tr>
<th></th>
<th>Investment Cost</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual Owners</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Large Shipping Companies</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

iii. Regulators

Studying the historical case study, it is seen that the role of changes in the regulatory arena (i.e. regulators’ actions) was not significant in altering the direction of change in the system. There were certainly some changes during the almost century-long transition period in the way naval transportation had been regulated. However, in the historical case studies considered, there is no indication of any regulation changes that brought in some advantage or disadvantage for a particular option. In that respect, we can assume that the regulation changes, hence the regulators, did not play an important role in shaping the transition trajectory. Therefore, there are no regulators represented in the model.

It should be noted that, the government is represented in the model, but not due to the role it plays as a regulator: it is represented in the model as a demand-side actor due to being responsible for the postal services.

iv. Opinion groups

Public opinion, or the position of the other indirectly involved social actors does not seem to be relevant for the decisions of the other actors in the system. Therefore, no social actor that acts as an opinion group is represented in the model.

An aggregation related decision in the actor representation process is the separate representation of different sub-groups within each actor role-type. However, the adequacy of representing each sub-group as a single collective actor in the model is difficult to justify considering the in-group heterogeneity and the potential importance of interactions between these actors. Therefore, each sub-group (e.g. luxury passengers) is represented by a set of actors in the model, which vary in priorities, information possessed, pace of decision change, and resources controlled. More detailed information about the composition of each actor group, and the number of actors within each group can be found in Appendix B.
e. **How to formalize the actors’ decision-making?**

The value function, and the component value functions that are used in this model are identical to the ones used for *WasteTrans*, which are discussed in Section 8.2. According to this formulation that is given in Equation 9.1, the value attributed to a decision option is the weighted sum of its performance in actor-relevant issues, where the weights represent the priorities of these issues for the actor.

\[ V_a(t) = \sum_i \lambda_i(t)v(x_{ait}) \]  

[9.1]

Using this formulation, the assessment values (i.e. \( V_{a,i}(t) \): assessment value for the option \( i \), calculated by the actor \( a \)) for each option and actor are calculated. Different from the previous case, two different decision formulations are utilized in this model.

The nature of the providers’ decisions is conceptualized as resource allocation decisions with a commitment effect. Each provider allocates its resources on two different lines of business; i.e. steam-based and wind-based. The shares of these lines in the total resources, in a way, represent the character of the shipping company, as it indicates the main line of business, for example. In this respect, the providers’ decisions are related to shifting their focus from one line to another. The formulation used for the shift in the investment in the model that is discussed in Chapter 8 (i.e. *WasteTrans*) suits such a conceptualization, and is also used in this model for representing the providers’ decisions. According to this;

\[ \frac{dI_{sail}(t)}{dt} = s_{steam,sail}(t) - s_{sail,steam}(t) \]  

[9.2]

where \( I_{sail}(t) \) represents the percentage of resources allocated to sail-ship option, and \( s_{i,j}(t) \) represents the shift from option \( i \) to option \( j \) at time \( t \), as specified before.

The decisions of the practitioner actors are conceptualized in a slightly different way. According to this, the decision variable in the model represent the aggregate consequence of a group of individual actors’ discrete choices on using a particular option (e.g. whether to travel by a steam-ship, or by a sail-ship? Which transportation option to use for a particular mail?). A variant of the well-known logit decision model (Ben-Akiva and Lerman 1985) is used to formalize this decision variable in the model. The corresponding equations are given in Equations 9.3 and 9.4;

\[ \hat{f}_{a,i}(t) = \frac{e^{V_{a,i}(t)}}{\sum_j e^{V_{a,j}(t)}} \]  

[9.3]

\[ \frac{df_{a,i}(t)}{dt} = \frac{\hat{f}_{a,i}(t) - f_{a,i}(t - dt)}{pdrd} \]  

[9.4]

where \( \hat{f}_{a,i} \) is the potential share of the option \( i \) in the total freight of the actor \( a \), \( f_{a,i} \) is the actual share, and \( pdrd \) is the potential demand realization delay. Similar formulations are used also for the allocation of demand in the postal services and in the passenger markets.
f. **How are the options characterized in the model?**

Considering the important issues for the actors, the two naval transportation options are characterized in terms of six major attributes; regularity of the service, average speed, operating costs, feasible range, investment costs and demand for the option.

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**g. Which mechanisms are ‘active’ in the analysis context?**

i. **Mechanisms related to option properties**

The steam-engine technology had a much wider application area than the naval transportation. Therefore, spillovers from other fields had been an important source of development. In that respect, an *exogenous change* mechanism is assumed to be active and effective for the properties that have technical characteristics, such as the average speed, and the investment costs. These mechanisms are assumed to be passive for the sail-ship option, since such spillovers were not expected. The penetration of new technological achievements is assumed to be dependent on (investment) resource flows for both of the options. The process that triggers technological development is competition: losses in the market share triggers motivation for technological development to become competitive. However, a development is only realized if there is some room for development (which can be changing via exogenously driven developments), and availability of resources allocated to the option. In summary, the properties with technical characteristics change as a consequence of these three mechanisms interaction. This interaction is formulized as follows:

\[
\frac{dx_{p,j}^{\text{feasible}}(t)}{dt} = \frac{x_{p,j}^{\text{max}} - x_{p,j}^{\text{feasible}}(t - dt)}{sdel}
\]

\[
\frac{dx_{p,j}^{\text{actual}}(t)}{dt} = \frac{x_{p,j}^{\text{feasible}}(t) - x_{p,j}^{\text{actual}}(t - dt)}{pdel} \cdot f\left(\frac{r_i(t)}{r_{ref}}\right) \cdot g\left(\frac{msl_i(t)}{msl_{ref}}\right)
\]

where \(x_{p,j}^{\text{feasible}}\) stands for the feasible level of the property for the option \(i\) (e.g. maximum speed possible with the latest steam-ships), and \(x_{p,j}^{\text{actual}}\) is the actual level of the same in the socio-technical system (e.g. average speed of the steam-ships active in the system). While \(sdel\) represents the time delay in technological spillovers, \(pdel\) represents the penetration delay of new technology under normal conditions. \(f(.)\) is the function used to represent the impact of resource flow on the technological development (i.e. ability to support technological improvement), and \(g(.)\) represents the impact of market share loss (i.e. motivation for technological improvement). The details of the formulation, as well as the non-linear effect functions of \(g(.)\) and \(f(.)\) are discussed further in Appendix B.

Other active mechanisms for the option properties are as follows; operation costs are assumed to decrease with increasing scale of the market (i.e. scale-driven development). Since range is dependent on the fuelling network for the steam-ships, it is assumed to improve over time with increasing investments (i.e. resource-driven development). Finally, the demand is a property that reflects the scale of the practitioners’ interest in a particular option. It changes as a direct consequence of the changes in this interest (i.e. scale-driven development).
ii. **Mechanisms related to actor perception**

The information possessed by the actors is assumed to be imperfect. The actors learn about the techno-physical properties of the options through external sources and their social neighbours (i.e. other actors belonging to the same actor group). The formulation used is identical to the information updating formulation given in Equation 8.4. Additionally, the information related to the disembodied aspects such as the demand/supply in the system flows through a social learning mechanisms; every actor broadcasts the capacity shortage or surplus in its own situation to the other actors with whom it interacts.

iii. **Mechanisms related to the actors’ behavioural identity**

In this model, the preference structures, hence the $\lambda_i$s in the value functions are assumed to be constant. Therefore, no mechanism related to the preference change is active in the model. The existing fleet of ships is considered as a serious economical and professional commitment for the providers. The scale of this commitment is assumed to prevent the actors from easily shifting to the alternative options. For example, a provider with a large sail-ship fleet is more likely to use its resources for improving the sail-ships rather than to immediately start building up a steam-ship fleet. The best available performance serves as the reference point in assessing the individual properties of the options. Therefore, these references change as the options improve, and as the actors learn about these improvements. In other words, the references for every issue for each actor are dynamic in nature.

9.3. **Sample simulations and analysis**

a. **Base run**

The model is initialized in order to represent the situation in the late 1800s. The steam-ship is defined as an option initially inferior to the sail-ships, but with a large room for improvement especially in the technological aspects. On the other hand, such improvement opportunities are defined to be restricted for the sail-ships based on the long established state of the option both in technical and practical aspects (i.e. the way shipping services are provided). The model output regarding the share of these two options in the naval transportation system is given in Figure 9.1, along with the corresponding empirical data. As can be seen, the model captures the change pattern with considerable pattern-wise and numeric precision.

When the processes that shape the model-generated dynamics are investigated, a battle between the property development mechanisms is observed. Figure 9.2 presents three feedback loops that operate on most of the properties of each option. This simplified causal-loop diagram (CLD) provides visual assistance for the discussion on the processes underlying the observed transition dynamics. Initially, having a large room for improvement (i.e. a strong L1), the steam-ship option experiences a gradual improvement especially in the techno-physical properties. This gradual improvement initiates the early demand shift to the steam-ships, which is initially slow. The postal service is the leading actor in this shift, since the steam-ships are assessed superior for this purpose due to their high regularity, despite inferior technical properties. In a sense, the postal services market becomes a market niche in which the steam-ship option can be nurtured. The luxury passenger market also provides a similar niche for the option at a later stage of the early development phase of the steam-ships. This early shift triggers two reinforcing processes; with more financial and capital resources
being available, the resource-driven change mechanisms are strengthened. This implies a faster property improvement via activating the resource-flow loop (i.e. \(L3\)) for the steamship option. Secondly, due to economies-of-scale the option also gains further advantage in the properties like the operating costs. As a result, these lead to a phase during which the option’s market share increases faster (or to the take-off phase in the transition). Especially, the developments in the range attract the long-range freight and the trans-Atlantic passengers towards the option, which can be considered as the steam-ship option penetrating into new market niches.
The story is quite different from the side of the sail-ship option. Being an established option, the development loop ($L1$) is very slow for most properties of the option, and is inactive for the others. The recognition of the upcoming competition and market share loss, the fight-back loop is activated in the sail-ship sector ($L2$). The size of the existing sail-ship fleet is an important factor in this development, since the providers choose to improve the sail-ship option, rather than shifting to the steam-ships in their operations. This leads to limited improvements in some properties. However, due to the limited room for improvement, the development driven by the fight-back loop, which prevents a rapid total defeat in the competition against the steam-ship option, ceases at some point. After that point, there is no mechanism that works against the penetration of the steam-ships to the whole system. Losing its market share, the sail-ships are confined almost only to the low value freight, and the emigrant passengers market niches.

### 9.4. Experimental simulations

Following the base simulation run, the model is used for further experimentation. Considering the historical nature of the case, these experiments clearly are not for developing future projections, or conducting policy experiments. The main objective is to use the model as a learning environment, and to develop basic insights about the internal dynamics of such a socio-technical system configuration. A set of these experiments is discussed below.

In the base run, the demand and supply for the steam-ships closely follow each other. Considering the historical commitments in economical and professional terms; what could have happened if the providers were slow in recognizing the steam-ships as a promising option, and in building-up a new fleet? Figure 9.3 presents the simulation results for such a setting. In order to avoid confusion, only the steam-ship side of the behaviour is plotted. The first of the series plotted is the actual market share of the steam option, whereas the second one is the desired market share (i.e. total market share of the actors willing to use steam-ships). The third line is the reference pattern from the base run. As can be seen, the actual market share of the steam-ship option is significantly different from the base run. Although

![Figure 9.3. Simulation output for the steam-ships in 'slow capacity build-up' experiment](image-url)
there is a growing demand for the option, due to a lack of sufficient capacity provision, the market share of the option does not change for a considerable amount of time. In other words, we observe a prolonged pre-development phase in the transition process. Since the level of utilization is much lower compared to the base-run, the performance improvement due to economies of scale is also less. Hence, the steam-ship cannot reach the economic performance level attained in the base run in the time horizon of the simulation, and the option captures less market share eventually.

Despite changes in the simulated behaviour, it can easily be seen that there is no fundamental change in the dynamics: following a longer pre-development period, the steam-ship option starts to gain dominance in the system as in the base run. Considering the conceptual model used, this is a natural consequence: the practitioners’ assessments of the available options are independent of the provisional properties of the options, such as delays due to capacity availability problems. Therefore, the reluctance of the providers in building a steam-ship fleet does not influence the demand on the practitioners’ side. In short, the practitioners are willing to wait for some available space in a steam-ship forever, and a possible prolonged wait does not change their opinion about the option. However, such an assumption can easily be challenged. In order to explore further, the model should be extended to cover plausible developments that could have been influential in such a case.

As an example of such an extension, it is assumed that the practitioners are sensitive to the demand-supply imbalance in the market. So, in the modified model, if the practitioners experience a capacity-shortage, their evaluation for the option worsens (i.e. bad reputation of the option due to prolonged waiting times). The simulation results with this modified version of the model are given in Figure 9.4. The figure includes two additional indicators, which show the ‘assessment score’ of the option averaged over all practitioner groups.

The indicator is a weighted average. In order to calculate this average score, the individual assessment scores of the actors are averaged using the market share of the actors as the weight.
a significant decline in the assessment of the option, and this stands as the main cause of the observed stagnation. In this case the provision system cannot keep up with growing demand, and this causes capacity crowding in the system. As a result the market share of the potentially superior option stagnates at very low levels, due to this crowding.

A further extension of this experiment leads to the behaviour given in Figure 9.5. In this version, it is assumed that practitioners ‘forget’ about the bad reputation of an option in time. In other words, a bad image due to a temporary capacity problem does not stick on to the option. The impact of the ‘forgetting’ mechanism can be seen both in the average score, and in the market share plots. After the growth in demand, the providers close the demand-supply gap for the steam-ship option, and catch up with the demand. Benefiting from this closure of the gap, and the forgetting mechanism, a fast recovery of the average score of the steam-ship option can be seen. This in turn triggers a second period of increasing demand for the steam-ships. In this version of the model, the time-lag between the demand increase and the capacity provision, and the forgetting practitioners are expected to yield a step-by-step transition to the steam-ships; i.e. transition as a sequence of multiple S-shaped market-share development periods.

In another set of experiments, the role of heterogeneity among the actors of the same role (e.g. practitioners) is investigated. Seven practitioner groups are separately represented in the model (i.e. disaggregated representation), based on the assumption that the differences between these groups play an important role in shaping the change dynamics. Alternatively, these groups could have been aggregated into a single collective practitioner actor (i.e. aggregated representation), averaging out the differences between groups. These experiments focused on the question whether some transition dynamics are significantly influenced by the differences, and cannot be captured by an aggregated representation, or not. A large set of simulations with different actor group compositions have been conducted for this purpose. The results show some particular transition patterns whose characteristics are dependent on the existence of heterogeneity among the actors, and cannot be explained with an aggregated representation. Instead of discussing the whole set of experiments, a demonstration case is
presented here to show such a particular pattern. A more extensive set of experiments related to this subject can be found elsewhere (Yücel and van Daalen 2008c).

In this demonstration case, the demand side of the system is initialized in such way that a moderately sized group (i.e. group A) already evaluates the steam-ship option as superior at the beginning of the run. There exists a second and bigger group (i.e. group B), which evaluates the steam-option as inferior. In order for this group to change its position, significant improvements are needed in a couple of dimensions (e.g. range and operating cost). The simulation output of this case is given in Figure 9.6. The rapid increase in market share in the early phase is mainly due to the immediate shift of group A actors to the steam-ship option. However, this shift does not constitute the critical mass that can yield the needed boost in the performance improvement via economies-of-scale. Once the whole group A actors shift to the steam-ship option, the growth in the market share stagnates. The new option is still underdeveloped for the group B actors, and it fails to attract a significant amount of demand from this group. Meanwhile, the option continues its development via other mechanisms such as spillovers, or development driven by the resources from group A. After a period of slow performance improvements, group B’s shift to the steam-ship option is initiated. This starts the second fast increase in the market share. In summary, the shift of an earlier group does not lead to the performance improvement enough to initiate the shift of the other group. A period of further performance improvement is required, which is the period of slowed-down growth in the market share in between fast growth phases. The resulting dynamic is a step-by-step (or terraced) transition.

9.5. Conclusions from the modelling study
The historical transitional change in the British naval transportation system is the second case used for investigating the extent of applicability of the proposed conceptual framework, and simulation-supported analysis approach. One of the primary objectives in conducting the modelling exercise is to explore the generality claim of the framework. In this respect, we considered whether the basic concepts and the mechanisms of the framework are also operational in the naval transportation context. The actor concept, as it is defined in the framework, served the purpose well in capturing the social aspects of the system, and it was especially appropriate for representing the critical heterogeneity in the demand for the
transportation services. Also the option concept was easily applicable for representing the shipping services in this specific socio-technical context. In addition, the general mechanism set of the actor-option framework allowed us to represent the key developments such as technological development, infrastructure build-up, and the incumbent option’s reaction to upcoming competition (the sail-ship effect).

Regarding the conceptual and practical limitations, we did not observe major issues during this experimental modelling study. This is closely related to the fact that this historical case can mainly be characterized by the developments in the techno-physical aspects of the system, such as the development of the used technologies, or the changes in the infrastructure that enables the provision of the options. This can be considered as evidence for the strength of the actor-option framework especially in this type of transition processes.

When we reflect on the purpose the model serves, there is an evident similarity with the case of the WasteTrans model: the model incorporates the hypothesis that is given in the descriptive case study about the key processes that drove the transition process. The model development and experimentation processes, hence, serve a testing purpose for the consistency of the given description, as well as for its sufficiency. As shown in Figure 9.1, the model generates the historical dynamics with considerable numeric and pattern-wise similarity. In that respect, the modelling process and the obtained results in the base run can be accepted as supporting evidence for the hypothesis given in the case study regarding the background developments underlying the observed transition dynamics. From this perspective, the way we use the model can be seen as another example of theory testing and development type.

However, the situation is significantly different in the additional experiments conducted with the model. In this latter stage, we loosen the ties of the model with the specific case of the British naval transportation system, and used the model as a general socio-technical system structure. In a way, the model represents a system where the provisions of the options are highly dependent on the providers’ capacity investments, and the British system serves as a benchmark for the model. Then, the model is used as a learning environment in order to develop some general insights about the configuration of a socio-technical system and the transition dynamics that this may lead to. Extension of the behavioural character of the actors by introducing waiting-time sensitivity and forgetting can be seen as examples of incorporating plausible behavioural patterns in order to conduct ‘what if…?’ kind of analyses. The conjoint dynamics of the demand and supply, and the role of the demand heterogeneity on the development trajectories of a novel option are two general issues we focus on. In summary, the way we use the model in this phase of the experiments can be considered as an example of using the models for general insight development.

The modelling study enables us to draw general conclusions on the basic premises of the framework (especially on actor disaggregation), and to develop insights on certain aspects of a transition process via the simulation experiments, and also via reflecting on the model structure, which serves as a generative explanation. The experiments clearly show that co-dynamics on the provision and the demand sides of the societal function/need are very important in shaping the observed transition patterns. Separation of the dynamics on these two sides makes it possible to study and to explain the changes on the provision side in relation to the demand-evolution, or vice versa. For example, a time lag between the demand formation,
and the provision system’s development is potentially a key issue leading to the limited penetration of a potentially superior innovation (i.e. an option that is shown to dominate the system if the provision system can keep up with the demand increase). Apart from capturing such dynamics, it is straightforward to reason about and explain these dynamics when both sides of the system can be monitored separately. This observation supports the utilization of different actor roles (e.g. practitioners, providers, regulators, opinion groups) to distinguish different social domains in a transition analysis.

Another observation is about the importance of the actor preferences’ distribution on overall transition dynamics. In cases where actors (e.g. practitioners) are heterogeneous in terms of their preferences, two very different cases are possible; balanced distribution, and distant clustering. This can be clarified on a simpler example on, for example, mobility practices. Figure 9.7 demonstrates an example of these two cases for a single attribute, where the x-axis represents the driving range, and the area underneath the curve represents the number of drivers willing to adopt a mobility innovation. In socio-technical systems where options are heavily influenced by resource- and/or scale-driven changes, these two cases may lead to very different dynamics. In the balanced distribution case, the transition is very likely to follow a smooth S-curve; i.e. the conventional depiction a transition process. However, in the distant clustering case, discontinuities may be observed along the transitional change process. The penetration of the innovation may stop well before the full diffusion, and in some cases, enter a second phase of penetration, which leads to a transition pattern constituted by consecutive S-shaped diffusion periods; i.e. terraced transition pattern. In cases where all the active development mechanisms are scale-driven ones, the novel option’s penetration in the system can stall in between these two clusters, and the option may never make it to the second big chunk of users, unless an external push is provided for the option’s development. The issue relates to the protection withdrawal decisions in the strategic niche management (Hoogma et al. 2002; Kemp, Schot et al. 1998), which can be the most important determinant of success or failure of the niche management experiment.

As a result, the aforementioned observation on the actor heterogeneity supports the importance of addressing the issue explicitly in models developed for analyzing transition dynamics: an issue that is highlighted in the basic premises of the actor-option framework. Additionally, these experiments, which lead to the identification of a non-conventional transition pattern, also demonstrate the possible contribution of simulation-supported exploration to the transition dynamics domain.
The Dutch Electricity System in Transition

The third modelling study that is conducted using the actor-option framework focuses on the Dutch electricity system. Differing from the previous two modelling studies, the subject is not an already completed historical transition, but instead probable transition trajectories that may be experienced in the Dutch electricity scene. As is the case of the two modelling studies reported in the previous chapters, the main objective is to demonstrate an application of the framework, as well as exploring its merits and limitations. Besides, in this specific case, we consider the framework in modelling a large-scale socio-technical system with a fairly complicated internal techno-physical and institutional structure. Additionally, we also aim to conduct a simulation-supported analysis on an ongoing transition, and demonstrate the type of conclusions that can be drawn from such an analysis. Considering the current contextual developments, which will be elaborated in Section 10.1, and the structure of the system, the Dutch electricity system constitutes a suitable case for these objectives.

10.1. Overview of the (ongoing) transition process

As already mentioned, this case is not a historical one. Therefore, the nature of the case overview is different from the ones given in Chapters 8 and 9. In this section, first, we discuss what is meant by an ongoing transition in this study. Following this, we present the contextual developments (i.e. the transition backdrop) related to the Dutch electricity system that makes us consider this system’s case as an ongoing transition.

a. Characterizing an ongoing transition

As discussed in Chapter 1, available definitions for a transition, however different in details, agree on the notion that a transition is a change of the system from its previous state/structure into a significantly different one. Such a definition, obviously, implies that identifying a transition is possible only by comparing the initial and the terminal structure/state of the system. Naturally, a clear identification of this sort is not possible for an ongoing transition. Therefore, dependent on what is understood as an ongoing transition, an ex-ante analysis of an ongoing transition is open to debate about whether there is a transition actually going on, or not. Due to this critical point, what is meant by an ongoing transition needs to be clarified.
A claim that a transition is in progress may stem from the belief that recently observed changes in the system are not temporary deviations from the previously dominant structure of the system, but are intermediate changes along a transition path leading to a fundamentally different system structure. In this case, the claim is based on the judgement in the permanency of the observed changes and the change process. Alternatively, such a claim may be grounded on the judgement that the current structure/state of the system cannot sustain its presence for long; hence a transition is inevitable in the close future. In this second case, the ongoing transition claim is based on the judgement that the system cannot preserve its currently dominant structure, and will have to change significantly. In these cases, by referring to an ongoing transition, it is implied that the system is changing or will have to change into a significantly different new structure/state.

The stance of this study is different from both of these cases while referring to an ongoing transition in the Dutch electricity supply system. Although an ongoing transition is mentioned, it is not claimed that a significantly different terminal state/structure is inevitable in the future. Hence, the possibility of the currently dominant structure/state’s prevalence is not ruled out, aiming to avoid a pro-transition bias. It is the observation of the contextual factors and mechanisms favouring a transition (i.e. a transition-friendly climate) in the current era that makes us consider the Dutch electricity case as an ongoing transition.

Simply put, an ongoing transition, in the way the term is used in this study, refers to an era during which contextual factors strongly favouring a transition are present, and the mechanisms/drivers of change within the system are active. In other words, it is a period during which a transition is likely to occur. Following this clarification about the ongoing transition notion, the following section will lay out the developments and factors that qualify the Dutch electricity case as an ongoing transition in this study.

b. An era of change for the Dutch electricity system

Since 1998, the Dutch system has been going through a significant institutional transformation from a vertically integrated structure to a liberalized market structure in accordance with the European Union electricity directives (van Damme 2005). This process involved restructuring the wholesale and retail markets, as well as establishment of new formal institutions and system actors. Although this institutional change did not have a direct influence on the physical infrastructure such as the distribution networks or the generator park, it altered the ownership and management scheme of this physical infrastructure (e.g. maintenance, decommissioning, investment, capacity commitment and dispatching). It is possible to trace the change at very detailed levels of system operation, but it should suffice to point out the change in the management mentality dominant in the system; the whole process resembles a gradual shift from a system operated by a central operator managing the system for cost minimization, to a system of independent actors operating their infrastructure for individual profit maximization. This high-level mentality change alone may be significant enough to yield a totally different mode of system functioning even with the identical physical infrastructure. Additionally, this shift will influence the way the infrastructure will evolve over time (de Vries 2004). However, due to the long delays typical to large-scale socio-technical systems, the impacts of this change on the infrastructure’s evolution cannot be immediate. Hence, despite the time passed since this institutional transformation, its impact on the physical infrastructure may not be visible yet, and will be more apparent in the following years.
A detailed survey of the generation park (i.e. the set of central electricity generators) reveals another fact that contributes to the transition-enabling climate. An important portion (around 20%) of the existing generation park consists of combined-cycle and conventional gas-fired plants commissioned during 1970s (Rödel 2008). These plants are already beyond their estimated lifetimes, and are expected to be decommissioned during the following decade. If the smaller-scale cogeneration plants and the coal-based generators close to the end of their lifetimes are also considered, the portion of the generation park to be decommissioned becomes even larger. In the case in which this loss is compensated by new capacity, an important change in the generation portfolio may be possible. On the other hand, if the loss is not compensated, the Dutch demand-supply capacity situation may experience its tightest levels in the last couple of decades. Additionally, coupling this fact about the room for change with the aforementioned mentality change in the system, next decade will be a period during which consequences of the mentality change on the infrastructure development will become much clearer.

Technological developments are also important. These include both the developments in the already utilized technologies, as well as the novel ones at the brink of commercialization. For example, the conventional combustion technologies are usually evaluated to be in their maturity stage with little room for development. In spite of this view, remarkable developments are being achieved in the efficiency and emission performance of the coal-based and the gas-based combustion technologies (Lako 2004; Rödel 2008). Besides these developments on the conventional technologies, there are new technologies and practices recently introduced or about to be introduced into the electricity generation scene. These include carbon capture and storage (CCS) (Smekens 2005; van den Broek et al. 2008), fuel cells (Martinus et al. 2005), novel biomass gasification and combustion technologies (Caputo et al. 2005), off-shore windfarms, and micro co-generators (m-CHP) (Faber et al. 2008; Pehnt et al. 2006), which may yield important changes in the way the electricity supply system is organized and operated.

Besides technological developments, changes in the energy markets, especially in the primary fuel markets, are also influential in the evolution of the Dutch electricity system. Natural gas-based generators currently dominate the Dutch system both in terms of generation and active capacity. However, during the last 15 years natural gas significantly lost its economic attractiveness as a primary fuel. As can be seen in Figure 10.1, the gas prices have almost doubled since 1990, whereas the change in the coal price is almost insignificant. The shift in the generation is already visible since the coal-based generators are getting a bigger share of the base load, while the share of gas-based generation is shrinking. In the long run, this price-related development may also lead to a significant shift in the generation portfolio keeping in mind the upcoming capacity renewal need mentioned above.

![Fuel Prices](image-url)
A change in the social sphere has also been visible during the past decade. At the state level, dedication for a more environmentally friendly, sustainable and secure system is apparent. The reflection of this dedication can be seen in the targets set by the government (e.g. 20% renewable electricity by 2020, Kyoto targets, 6 GW off-shore wind energy capacity), and also in the regulatory domain by the increasing number of regulations and governance schemes being introduced in order to achieve these targets (e.g. emission trading scheme, green certificates). A change along similar lines is also taking place at the end-user level; environmental concerns are on the rise against the economic criteria that can be claimed to dominate the end-user behaviour in this context up until now. For large industrial consumers, it’s the increasing value of the environmental friendliness notion in the market value of the firm and its products that brings the ‘green’ alternatives on to the table. In short, an increase in the environmental values, whatever underlying driver may be, is apparent. The end-users did not have much option apart from the central grid in terms of electricity sources until the past decade. However, green electricity, small- and medium-scale distributed generation options are now available as novel alternatives. The impact of such developments may be expected to have an influence on the evolution of the electricity system.

It can be seen that the Dutch electricity system is going through an era during which significant changes in multiple dimensions, such as technological, social, infrastructural, regulatory and economic, are taking place. The co-existence of these developments is what makes the current era a suitable one for a transition. It is possible to claim that interactions of these dynamics in different domains are causing alternative development trajectories to emerge for the electricity system. However, whether the system will shift to a newly emerging trajectory, or not is not apparent. Simply put, if the Dutch system is to shift to an alternative path from the one it is in, it will most likely take place in the following couple of decades. Otherwise, significant changes within the current development path may be expected, which may lead to important changes in the current configuration of the system, but not leading to a significantly different novel one. In other words, a ‘regime transformation’ may take place (Geels and Kemp 2007; Geels and Schot 2007). In the light of these observations, we consider the case as an ongoing transition in the sense that is specified in the previous section.

10.2. Model description
This section provides a brief overview of the model, i.e. ElectTrans, that is developed for exploring probable transition trajectories for the Dutch electricity system. The model builds upon the concepts introduced in the actor-option framework, and a brief overview of the model is given in the following sub-sections. A more detailed description of the model can be found in Appendix C.

a. What is the function/need of concern?
Supply of electricity is the function that characterizes this case. The scope of the analysis is national. In other words, the analysis is confined to the Dutch electricity system. The time horizon of the analysis is considered to be the 30-year period from 2010 to 2040.

b. Which aspects of the societal function characterize the transitional change?
We are concerned with two issues related to the national energy system in this analysis. The first one is the carbon-dependence of the system, which is closely related to the environmental
performance of the system. The fuel mix, and the aggregate carbon emissions are the basic indicators to monitor with regard to this first issue. The second issue is related to the overall generation structure of the system; i.e. centralized vs. distributed generation. We monitor the share of the distributed generation in the system to track changes related to this second issue.

c. **What are the alternative means of fulfilling the societal function?**
The options in this model are the alternative sources of electric power for the end-users. Two major classes of *options* (or sources for electric power) are relevant in this context; central grid, and distributed generators\(^1\). The end-users can satisfy their power demand through the electricity supplied via the central grid, or use a distributed generation device/facility to self-generate power. It is possible to recognize different options within these two option-classes. Table 10.1 summarizes the options explicitly covered in the model, including both the grid-based and the distributed ones. It is clear that not all of these options are appropriate for any end-user, since the end-users include individual households, as well as industrial facilities. This issue is recognized in the model, and we will come back to the issue when we discuss different actor-types in the following sub-sections.

<table>
<thead>
<tr>
<th>Grid-based options</th>
<th>Distributed generation options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Electricity <em>(Gray)</em></td>
<td>Biomass Combustion</td>
</tr>
<tr>
<td>Grid Electricity <em>(Green)</em></td>
<td>Biomass Gasification</td>
</tr>
<tr>
<td></td>
<td>CHP (Gas Engine)</td>
</tr>
<tr>
<td></td>
<td>CHP (Gas Turbine)</td>
</tr>
<tr>
<td></td>
<td>Micro-CHP</td>
</tr>
<tr>
<td></td>
<td>PV Roof</td>
</tr>
<tr>
<td></td>
<td>Wind Farm (Inland)</td>
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<tr>
<td></td>
<td>Wind Farm (Off-shore)</td>
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<tr>
<td></td>
<td>Wind Farm (On Shore)</td>
</tr>
<tr>
<td></td>
<td>Wind Turbine (Inland)</td>
</tr>
</tbody>
</table>

**Table 10.1. Electricity supply options for the end-users in ElectTrans**

d. **Who are the major social actors in the system?**

i. **Users/Practitioners:**
These are the end-users who demand/consume electric power in the system. We encounter three main user categories in various reports on electricity consumption, which are given in Figure 10.2 with their shares in total consumption in 2007. The ‘other’ group in the figure includes the commercial enterprises as well as horti-/agricultural enterprises, like the greenhouses. Since the demand patterns as well as preference structures of these two groups are not expected to be very similar, clustering them in a single category is evaluated to be inappropriate for the purposes of this study. Therefore, four groups of end-users are represented in the model, which are industrial users, commercial users, horti-/agricultural users, and households. The current shares in electricity use of the actor groups used in the model are given in Table 10.2.

The practitioners are relevant in the context of demand formation, and the adoption of distributed generation capacity. Therefore, important aspects such as the actors’ seasonal demand patterns, and the generation capacities they possess are explicitly represented in the model. Based on the data obtained from CBS Statline database (CBS 2010), the distributed

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\(^1\) The terms ‘distributed generator’ is used similar to the sense it has been defined by Pepermans et al. (2005). Briefly, a distributed generator is defined to be a generator that is not dispatchable by the central system operator.
generation capacity owned by the actors consists mainly of cogeneration units and wind turbines as of 2006 (see Table 10.3). The amount of the generation capacity owned by the practitioners is initialized based on these figures.

In the way it is conceptualized in the model, the primary decision to be made by an end-user is about getting the electricity from the central grid, or self-generating electricity by adopting distributed generation options. For the grid-based sources, this is done via supply contracts, and in the case of distributed generation, it corresponds to generation-capacity adoption. There are two grid-based options in the model: gray electricity and green electricity. In case the end-user opts for owning distributed generation capacity and self-generating electricity, various options are available, such as wind turbines and gas engine CHPs. Table 10.4 provides the aggregate list of the supply options, including both the grid-based and the distributed generation ones, available in the model, as well as their appropriateness for the individual actor groups.

As a consequence of the power-demand allocation decisions, the end-users directly influence the distributed generation capacity in the system, as well as the amount and the pattern of the power load on the central grid. As mentioned earlier, these demand allocation decisions are
not simple economic ones made based on cost figures, but they are multi-dimensional ones where environmental and social issues also play a role. The actor groups consider four criteria in the decision process; cost of supply, price volatility, environmental performance, and in-group familiarity. Among these criteria, the environmental performance refers to direct CO₂ emissions caused per kWh electricity generated by the evaluated option, and the familiarity refers to the diffusion of the option within the actor group to which the actor belongs. The weights of these criteria for an actor specify the individual preference structure of that actor, which is the main factor that differentiates the decisions of the actors when they are exposed

Table 10.4. Electricity supply options for the end-user groups in ElectTrans

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Households</th>
<th>Agricultural Users</th>
<th>Commercial Users</th>
<th>Industrial Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Electricity (Gray)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Grid Electricity (Green)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Micro-CHP</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PV Roof</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>CHP (Gas Engine)</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CHP (Gas Turbine)</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CHP (CCGT)</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Biomass Combustion</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Biomass Gasification</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Turbine (Inland)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Farm (Inland)</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Farm (On Shore)</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Farm (Near shore)</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wind Farm (Off-shore)</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓: Option appropriate/usable for the actor type
✗: Option not appropriate/usable for the actor type

Table 10.5. Relative importance of decision criteria for actor groups

<table>
<thead>
<tr>
<th></th>
<th>Households</th>
<th>Agricultural Users</th>
<th>Commercial Users</th>
<th>Industrial Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of supply</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Price Volatility</td>
<td>o</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Environmental Friendliness</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>o</td>
</tr>
<tr>
<td>Familiarity</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>o</td>
</tr>
</tbody>
</table>

o: Not important/relevant
+: Important
++: Very Important
+++: Extremely Important
to identical option sets. The relative weights of these four criteria for each actor group are given in Table 10.5. The specific values of these weights for the base case, and the scenarios are given in Appendix C.

It is important to note that due to the scale of the system being considered, the number of the social actors in the actual system is very large. For example, in the smallest user group, which is the industrial users group, the number of end-users is above 40000. This brings about the need for aggregation. Therefore, the end-user agents\(^2\) in the model represent a group of real-world actors, rather than individual ones.

### ii. Providers

By definition, the providers are the main actors in the provision system, which is related to the implementation of an option and to sustaining its functionality. For the distributed generation options (i.e. all options except grid-based gray and green electricity supply), the actors who control such a distributed generator is assumed to be the key actor for this provision system. In other words, once an end-user installs a distributed generator, this end-user also obtains a provider role: the actor becomes a power provider, but mainly for the actor’s own needs. For the grid-based options, the actors responsible for the options’ provision operate at the national level, and play a key role in the development of the electricity supply system. Most important of these actors are the generation companies. These actors are mainly responsible for the short-term operation of the generators they possess, as well as the long-term management of their generator parks (i.e. generation capacity investments). Seven of these actors are introduced into the model, corresponding to the large generation companies in the Netherlands. These providers are important to the system with their portfolios of generation plants (i.e. generator park), which constitute the major techno-physical component of the provision system of the grid-based options.

The Dutch generator park consists of around 60 active generators with generation capacities from 15 MWe to 695 MWe (Rödel 2008; Seebregts 2005). The generators also show variation regarding the generation technology utilized; hence the primary fuel used. As of 2006, 28% of the active generation capacity was coal-based, whereas 69% was natural gas-based. The Borssele nuclear plant constituted 3% of the Dutch central generation capacity (Figure 10.3).

Besides these already operational generators, a set of new generators is already in the permission or construction phase. According to TenneT (2007a; 2007b), an additional 10000 MWe of capacity has been planned by the generation companies. These new generators are announced to be operational by 2014. Approximately 40% of this new capacity is natural gas-

\(^2\) As described in Appendix C in detail, *ElectTrans* is a multi-agent simulation model. We use the term ‘agent’ for the components of the model that represents the state and behavior of real social actors.
based, whereas the remaining 60% is coal-based. The generation companies have already made connection agreements with TenneT for 60% of this additional capacity, which constitutes a portion less likely to be cancelled during the process.

All generation plants active as of 2006 are initialized using the technical and economic characterization reported in Rödel’s dissertation (2008), and assigned to the provider agents in the model. The status of these plants is set to be active. Additionally, the expected capacity expansions reported in the TenneT reports (2007a; 2008) are also included in the model. Among these, the generators for which connection agreements have already been made are given the status under-construction. For the remaining projects, which have been announced but no connection agreements been made, the generator status is set to be announced. The list of individual generators included in the model, including the technical and economic properties specified for them, is given in Appendix C.

The short-term operational decisions of the generation companies involve the unit commitment decisions, and the price bidding in the electricity market, which are directly related to the dispatching of the load to the generators. In the context of dispatching, the generation companies declare if a generation unit will be online during a certain period (i.e. whether the generation unit will be committed), and bid a threshold price above which the company is willing to generate electricity using that particular unit (i.e. price bidding). In the way generation companies are conceptualized in the model, they are assumed not to be acting strategically. This implies two assumptions related to load dispatching. Firstly, it is assumed that they will not withhold generation capacity for strategic reasons, as it is discussed to be plausible in oligopolistic markets (Green 2004). Therefore, as long as a generator is available for generation, it is committed to generation with full capacity. Secondly, it is assumed that there is no inter-actor cooperation in price bidding to increase the prices, which is possible due to low price elasticity of the power demand.

The second important role of the generation companies in the evolution of the central supply system is via their long-term capacity management decisions, i.e. the investment and decommissioning decisions. The generation companies periodically make an assessment of the individual units in their generator park. In this assessment, the decommissioning decisions are mainly based on the expected lifetime of the technology used in a generation unit. A unit at the end of its lifetime is decommissioned. Additionally, an old unit close to its lifetime may also be decommissioned if the unit has been making loss over the last 3 years.

The generation companies’ capacity expansion decisions are mainly driven by profit expectations. In other words, it is assumed that the generation companies have a single objective and are pure profit-seekers. The capacity expansion decisions are dependent on four basic pieces of information; forecasts about the fuel prices, forecasts about the demand, forecasts about the active set of generators connected to the grid, and information about the feasible investment options.

Each agent representing a generation company in the model is equipped with a memory, which keeps record of the past market developments. The time scope of this memory is determined by a parameter, i.e. memory horizon, in the model, and is set to be 5 years in the base version of the model. The information traced by the agent includes the fuel prices, seasonal load levels,
average electricity prices, and other revenue related quantities, such as the market prices for carbon emission permits or the green certificates. Based on the information in this memory, the agents develop future estimates for the key variables (e.g. fuel prices, load levels, green certificate prices) to be used in their investment decisions.

Considering the load dispatching process, it should be clear that the generation level as well as the revenue to be made in a period by a generation unit is strongly dependent on other active units. Hence, the expected set of active generation units in the future is an essential element in evaluating the expected profit to be made with a new unit. In that respect, the agents examine the current generator park, and develop their own expectations about the future state of it. In this process, they consider plausible decommissioning of the old plants, as well as commissioning of new generators already announced or under-construction. The agents are assumed to possess perfect information about the announced and under-construction units. This is a reasonable assumption since the generation companies get some informal information about the intentions of the other companies due to the permission applications, and more importantly TenneT already makes these plans public in its reports.

Forecasts regarding the market conditions as well as the generation park are used to create an expected future state of the supply system for the agent. The agent evaluates the available investment options within this expected state. In order to do so, the agent iterates over all available options, and runs the dispatching algorithm for each of them to estimate generation volume and revenue that can be realized within this expected system state with the option considered. This estimated generation volume constitutes the forecasted basis for fuel costs, and variable operation and maintenance (O&M) costs. The estimated revenue is used in the feasibility analysis besides these costs. Combining these figures with investment and fixed O&M costs, the agent comes up with a return on investment (ROI) estimate for each option (Pirog et al. 1987). The option with the highest ROI is selected for investment. If the highest ROI is less than the expected ROI of the agent, which is 15% in the base case, the agent does not make any investment for capacity expansion.

As in the case of unit commitment, it is assumed that the generator companies are not acting strategically in their investment decisions. Therefore, they only invest when there is room for profit. Strategic behaviours that are plausible in oligopolistic electricity markets such as overinvestment for preventing new entrants, or inter-actor cooperation for underinvestment in order to increase the prices are not covered in the current version of the model.

The generation unit options that are available for investment in the model are given in Table 10.6. Each option has a pre-specified generation capacity, which is derived from the common commercial sizes (Breeze 2005; Rödel 2008).

A third decision that providers make about their generation park is related to biomass co-firing. Most of the existing coal-fired generators can also use biomass-coal mixtures (up to 10-15% biomass) without significant loss of efficiency (Caputo, Palumbo et al. 2005; van den Broek, Faaij et al. 2008). The agents representing the generation companies check the additional cost of shifting to co-firing against the additional benefits, and make a fuel choice (coal alone, or biomass co-firing) for the coal-fired generators.
Besides the generation, the other two important aspects related to the grid-based supply options are the transmission and the distribution. However, since the main objective of this study is more focused on the generation part considering the transition-characterizing aspects; i.e. fuel mix and role of central generation. Due to this, the network developments are excluded from the model. In doing so it is assumed that the network will not constitute a constraint on the supply from central generators, and it will be possible to transfer electricity between any supply and demand points in the system without major implications. This latter assumption is also referred to as ‘copper plate’ assumption (de Vries 2004).

An important actor with regard to the grid-based provision system is the system operator, who is responsible for demand-supply balancing in the system (TenneT in the Netherlands). In the current technological setup of the central supply system, it is not possible to store electricity. Therefore, electricity has to be generated in real-time with the demand for it. The decision of which units are going to generate electricity to supply a given demand is referred to as load dispatching (or capacity dispatching). The dispatching is done by a central authority/institution in order to achieve the maximum economic efficiency. This means supplying the demanded electricity with the least total system cost. The system operator, as it is depicted in the model, is responsible for the dispatching task. This actor collects the price bids from the generator actors for each generator unit they have, and the system operator calls the units for generation according to increasing price bids (i.e. merit order) until the demand is met.

### Table 10.6. Investment options available in the model

<table>
<thead>
<tr>
<th>Option Name</th>
<th>Capacity (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC (Single unit)</td>
<td>400</td>
</tr>
<tr>
<td>PC (Double unit)</td>
<td>800</td>
</tr>
<tr>
<td>PC (Single unit) with CCS</td>
<td>800</td>
</tr>
<tr>
<td>IGCC</td>
<td>300</td>
</tr>
<tr>
<td>IGCC with CCS</td>
<td>300</td>
</tr>
<tr>
<td>Gas Turbine</td>
<td>50</td>
</tr>
<tr>
<td>Gas Turbine CHP</td>
<td>50</td>
</tr>
<tr>
<td>CCGT (Single unit)</td>
<td>400</td>
</tr>
<tr>
<td>CCGT (Double unit)</td>
<td>800</td>
</tr>
<tr>
<td>CCGT SOFC</td>
<td>400</td>
</tr>
<tr>
<td>CCGT (Double unit) with CCS</td>
<td>800</td>
</tr>
<tr>
<td>CCGT CHP</td>
<td>200</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1000</td>
</tr>
<tr>
<td>Wind farm</td>
<td>20</td>
</tr>
<tr>
<td>Wind farm (Off-shore)</td>
<td>100</td>
</tr>
<tr>
<td>Biomass/Waste Fired</td>
<td>10</td>
</tr>
</tbody>
</table>

**PC**: Pulverized coal, **CCS**: Carbon capture and storage, **IGCC**: Internal gasification combined cycle, **CHP**: Combined heat and power, **CCGT**: Combined cycle gas turbine, **SOFC**: Solid oxide fuel cell
In summary, the provision system covered endogenously in the model consists of a set of generator agents representing the generation companies who are responsible for short-term operation and the long-term capacity management of the generation capacity, and a single system operator who matches the power load with the generation capacity in the system.

### iii. Regulators

Despite not having a direct influence on the infrastructure or the generator park, the state or related public institutions play an important role in the evolution of the electricity system. This happens via taxes, subsidies, or introduction of market-based mechanisms, such as carbon pricing. Since these indirect interventions play an important role in shaping the transition path, they are also covered in the model. A single regulator actor is included in the system in order to represent the state's intervention to the electricity system. The actor decisions are mainly related to the amount of tax/subsidy to be given to particular classes of power generation options.

The Netherlands committed to the goal of increasing the share of renewable electricity generation, and the recent goal is declared as having 20% of the total electricity from the renewable sources by 2020. In order to achieve this target, several policies have been used since the early 1990s. Despite having a meta-direction of greening the electricity supply, the Dutch government's preference has been towards generic policies, which do not focus on specific technologies or applications. Both supply-side (e.g. investment support, or feed-in subsidies) and demand-side (e.g. taxing gray electricity) policies have been utilized so far. However, the demand-side policies are not used anymore, and the focus seems to be on boosting capacity investments via the supply-side policies operationalized via the SDE\(^3\) program (SenterNovem 2009a; SenterNovem 2009b; SenterNovem 2009c; SenterNovem 2009d). Implementations of these policies showed significant variation within short intervals, which caused the Dutch renewable energy policy not having the best consistency record compared to some other EU countries like Germany or Spain (Agnolucci 2007; Junginger et al. 2004; van Sambeek and van Thuijl 2003). This can be interpreted as high uncertainty in the regulator's behaviour at policy implementation level. Since it is almost impossible to endogenously imitate such a policy implementation behaviour, which lacks consistency, a simpler approach is employed: it is assumed that the Dutch government will continue supporting capacity development in renewable electricity generation via increasing the economic competitiveness of the renewable generation options, which is the main objective underlying various support policies recently employed. As a result, the regulator agent in the model is instructed to compensate renewable generation capacity via paying a subsidy per kWh electricity delivered to the grid, which is equal to the gap between the average market price of the electricity and the cost of generation via that specific option.

### e. How to formalize actors’ decision making?

#### i. End-users (practitioner/user)

A variant of the *logit* function (Ben-Akiva and Lerman 1985; Gensch and Recker 1979) is used in determining the shift of end-user demand among electricity supply options. Due to aggregation, the model agents represent large groups of actors as mentioned before. The aggregation of discrete decisions of such a large group converges to a continuous process, and

\[3 \text{ Stimulating sustainable energy production (i.e. Stimulering Duurzame Energiproductie, in Dutch)}\]
a demand allocation formulation that represents this continuous change in the actors’ choices is used. At the end of each year, a free demand for each agent is calculated, and this demand is allocated among the feasible options. The free demand is equal to the sum of two terms. The first of them is the total demand satisfied, during the previous year, via the distributed generation capacity being depreciated, or the grid-based supply contract being expired (i.e. replacement component). The second term is equal to the growth in the demand of the agent (i.e. expansion component). The functions used to determine the allocation of this free demand is given in Equations 10.1 through 10.4.

\[
\tilde{a}_{i,j} = \frac{a_{i,j} - \hat{a}_j}{\hat{a}_j} \quad [10.1]
\]

\[
u_i = \prod_{j=1}^{4} e^{\alpha_j \tilde{a}_{i,j}} \quad [10.2]
\]

\[
U = \sum_{i=1}^{n} u_i \quad [10.3]
\]

\[
s_i = \frac{u_i}{U} \quad [10.4]
\]

\[
\tilde{a}_{i,j} : \text{Normalized attribute } j \text{ of option } i
\]

\[
a_{i,j} : \text{Attribute } j \text{ of option } i
\]

\[
\hat{a}_j : \text{Reference level for attribute } j
\]

\[
u_i : \text{Expected utility from option } i
\]

\[
\alpha_j : \text{Weight of attribute } j \text{ for the actor}
\]

\[
U : \text{Total utility over all options feasible for the actor}
\]

\[
s_i : \text{Share of actor’s free demand allocated to option } i
\]

Conventional gray electricity is accepted as the base-option in the model; hence the attributes of the grid-supplied gray electricity constitute the reference levels for the attributes. In the case of grid-supplied options, the demand allocated to the option represents new supply contracts. For other options, it indicates the need for capacity investment in that option. The generation capacity to be installed by the end-user is equal to the capacity that can supply demand allocated to the option based on the technical properties of the option (e.g. seasonal availability). This way, the end-user groups manage their portfolio of supply sources, either by renewing the grid-based supply contracts, or installing distributed generation capacity.

**ii. Generation companies (provider)**

The agents that represent the generation companies utilize an adaptive trend estimation and univariate trend extrapolation heuristic to develop their future estimates regarding the key variables. In the adaptive trend estimation, new information perceived by the agent at the end of each simulation step is used to update the historical average, and trend information. When necessary, this average and trend information is used to develop a forecast via simple extrapolation. It should be noted that, in implementing such a heuristic it is not claimed that the actual generation companies are using a forecasting approach this simple. However, Sterman demonstrates that this heuristic imitates the forecasts developed by the electricity utilities with a significant success (Sterman 1988). The adaptive trend estimation and extrapolation heuristic used in this model is given in Equations 10.5 through 10.8;
How are the options characterized in the model?

Considering the issues relevant for the end-users in their decision regarding which options to utilize, the supply options are characterized by their economical, technical, and social attributes. Economical attributes include investment and operating costs for the distributed generation options, and prices per kWh electric for the grid-based options. Technical attributes are mainly related to the environmental performance, and relates to the emissions caused per kWh via using a certain option. The technical and economical attributes used for the generation options covered in the model are given in Appendix C. The social attributes of the options are related to the intensity of use, and the past experience with a particular option in a given end-user class.

Which mechanisms are ‘active’ in the analysis context?

Mechanisms related to option properties

When we consider the available electric power sources for the end-users, it is clear that the grid-based and the distributed generation-based options have very different natures. Hence, the mechanisms that alter the end-user-relevant properties of these two types of options are also different.

The economical attributes of the grid-based options, such as the cost of electricity per kWh, are mainly dependent on the power load on the grid, and the active generation park. The power load is dependent on the instantaneous scale of the end-user demand, hence changes in a scale-driven manner. The generator park, on the other hand, develops as a consequence of the investments of the generation companies (resource-driven change). As a result, the economical attributes are influenced simultaneously by two active mechanisms one being driven by the end-user demand, and the other one by the investment resources of the generation companies.
The technical properties of the grid-based options (e.g. \( \text{CO}_2 \) emitted per kWh delivered) are also dependent on the state of the generator park, which changes through the investments of the generation companies (resource-driven change). These investments correspond to the adoption of the state-of-the-art generation technologies. Clearly, the state-of-the-art in generation technologies cannot be assumed to stay constant during a time horizon of 30 years. The state-of-the-art is assumed to develop in an exogenous manner, and improve during the time horizon of the analysis. The rate of this development is proportional to the gap between the current level of the attribute and the plausible future levels. In other words, the development rate is defined to be proportional to the room-for-development. Current and plausible future values for the technical (e.g. electrical efficiency, availability) and economic attributes (e.g. investment cost, fixed O&M cost) of the options are determined based on recent studies on the issue (Davison 2007; Lako and Seebregts 1998; Rödel 2008; Seebregts 2005; van den Broek, Faaij et al. 2008; Vogstad 2004; Voorspools 2004; Voorspools and D’haeseleer 2003), and reported in Appendix C.

Besides the aforementioned developments in the technical attributes of the existing options, there are also discrete changes in the option set, which can be considered as novel options being economically available. Although the set of options given in Table 10.6 is included in the model, not all of them are available for investment in the beginning of the time horizon of the simulations. All the options with CCS are assumed to be available for investment after 2025, considering the legal and technological progress required. In the base run of the model, it is also assumed that the informal position of the Netherlands regarding nuclear energy (i.e. no further nuclear installations) will stay intact.

The major developments in the distributed generation technologies are assumed to be beyond the influence of the Dutch market. Therefore, the technical, and the economical properties develop through exogenous change mechanisms. In formulating the exogenous development of an option, it is assumed that the development will continue with a decreasing rate, and the corresponding property will eventually converge to a pre-defined future value. The specific values of the initial, as well as the expected future values for the technical and economical attributes of the options are given in Appendix C. In specifying these initial and final values, data introduced in (Breeze 2005; Caputo, Palumbo et al. 2005; Freris and Infield 2008; Junginger, Agterbosch et al. 2004; Lako and Seebregts 1998; Martinus, Blesi et al. 2005; Seebregts 2005; Voorspools 2004) are taken as the basis.

\[ \text{Mechanisms related to actor perception} \]

The end-users are assumed not to have real-time and perfect information about the developments regarding the electricity supply options. Regarding the grid-based options’ attributes, there is no direct experience of the end-users with the generation process. Therefore, the end-users’ perception about the grid-based options mainly change through learning from external sources. For the distributed generation options, all three learning mechanisms, i.e. individual, social and from external sources, are relevant. The actors can enhance their information about an option faster compared to the exogenous learning alone, if they or other actors in their category adopt and use the option.

The generation companies rely on information they have about the technical and economical properties of the available options, such as electrical efficiency, availability, and variable
O&M costs. The actors are not assumed to possess perfect information about these attributes. Therefore, the actual properties of the investment options, and the information available to the actors about these properties are differentiated in the model. In the implementation, the actors learn about improvements in the actual properties of options with an information delay, which determines the pace of learning from an external source (e.g. technical reports). This holds for learning about developments in the properties of the options. In the case of a totally new option being available (e.g. CCS), it is assumed that the generation companies learn about its availability almost in real-time, though with imperfect information about the attributes of this new option.

### iii. Mechanisms related to actor identity

For the end-users, the grid-supplied gray electricity is assumed to be the reference option. This implies that an option is evaluated based on the difference of its (economical or environmental) attributes from the ones of the grid-supplied gray electricity. Considering that the economical and environmental properties of this reference option are dynamic, it is clear that the reference formation mechanism is active in the model; every time the properties of the reference option change, the references of the end-users are adjusted accordingly with some delay. The generation companies act mainly based on economical concerns, and they utilize a fixed economical reference point for judging profitability of possible investment. Therefore, the related references of the generation companies are constant in the model.

In this capital-intensive system of electricity supply, the former capacity investments constitute the most important commitment for both the end-users, and also the generation companies. The existing generation units do not allow the generation companies to shift between alternative technologies, or fuel types freely. The same holds for an end-user who owns distributed generation capacity. In that respect, capacity investments of both actor types trigger commitment formation, which creates inertia for the actors in changing their courses of action.

Considering the time horizon of the analysis along with the increasing environmental and economical concerns, it is quite plausible to observe significant changes in the actors’ preferences, both on the end-users and the generation companies’ sides. Therefore, the preference change mechanisms are relevant and important in the context of this modelling study. Although these mechanisms are set to be passive in the base simulation of the model, in the scenario experiments the preference structures of the actors are modelled to be variable.

### 10.3. Sample simulations and analysis

The model introduced in the previous section, i.e. ElecTrans, is initialized in correspondence with the state of the actual system in 2006. Prior to full-scale experimentation, a thorough verification and validation process is conducted in order to assess the appropriateness of the model. Verification process, simply, covers the assessment of the model in terms of implementation problems (i.e. precision in converting the conceptual model to the computer environment). In this case, it is conducted via extensive code walk-through tests, as well as input-output tests for isolated sections of the model. Validation involves the assessment of the model structure as well as the model behaviour. The structure of ElecTrans is validated via several tests, such as isolated behaviour plausibility, and extreme value tests. However, an
extensive behavioural validation was not possible due to the inappropriateness of the historical data from the actual system for such a procedure. Since the Dutch electricity system has been going through an important liberalization process, the historical data before and after this process is generated by different system structures. Since ElectTrans corresponds to the post-liberalization structure, historical data from the pre-liberalization period is not a meaningful input for a behaviour validation test. Therefore, only a limited behaviour validation procedure could be conducted.

Considering the technological, social and economical aspects, ElectTrans provides an environment for a wide range of experiments. Only a limited subset of such experiments, which is selected on the basis of contextual and methodological relevance, is reported in this chapter. First of all, it is aimed to present the plausible directions of change for the Dutch electricity system under commonly discussed developments, such as the rapid improvement of clean coal technologies, or the policy interventions leading to more expensive carbon emission permits. The methodological relevance is more about linking back to the actor-option framework. The electricity supply system has a fairly complicated system structure in terms the way it is organized and it functions. Additionally, a change in the system may be driven by several different developments such as the introduction of new options, change in the attributes of the existing options, change in the preference structures of system actors, and change in contextual factors such as fuel prices and regulations. During the experiments with the model, we aim to explore the extent to which the model can serve for studying the impact of such changes in the differing aspects of the socio-technical system. As will be apparent in the discussions, the simulation results are not considered as future predictions for the Dutch electricity system, but these results are used to develop a better understanding about the way the Dutch electricity system may react to particular type of changes.

For each case to be discussed below, multiple simulation replications are performed. This is mainly due to procedural processes related to the agent-based simulation that are probabilistic in nature, such as shuffling the order of the agents before each decision round. In order to filter out the impact of such probabilistic processes on the conclusions to be drawn, 50 replications are performed for each case, and the mean values of these replications are presented during the discussions, unless otherwise indicated. The parameter values used for each case are provided in the technical appendices, as well.

a. **Base case**

This case constitutes a basis for comparison for the analysis. The case assumes the continuation of the recent trends with no major changes. In relation to technology, this translates to a normal technological development pace, as well as a normal innovation climate. All generation technologies available in the beginning of the analysis period are assumed to develop according to the widely accepted trajectories. In other words, their technical and economical properties, such as investment cost or electrical efficiency, converge to the most likely values discussed in the literature. Also no significant shift in the commercial introduction of new options, such as carbon capture and storage, is expected in the case. The context in which the end-users and the generation companies act is mainly defined by the fuel prices and the regulations in the model. Regarding the fuel prices, it is assumed that the coal and natural gas prices will follow their historical growth averages. Initial fuel prices and corresponding yearly increase percentages are given in Table 10.7.
The regulator is assumed to continue supporting the renewable generation options according to the currently dominant perspective of making them economically competitive against the conventional technologies. Uncertainty is quite high regarding the evolution of the carbon permit-related policies beyond 2012. Both the commitments on total emissions as well as the national permit allocation schemes may undergo significant changes, or may stay as it is currently. In the base case, no significant change is assumed. In accordance with that, the emission permit prices are assumed to continue to settle around the current insignificant levels (i.e. below 10 Euro/ton CO$_2$).

No significant change on the end-users’ side related to the norms and priorities is expected in this experiment. Therefore, the preference structures, which are represented by the weights of different objectives as discussed before, that guide the actions of these actors stay the same throughout the simulation run.

The base version of the model is simulated for the 2010-2040 period. The dynamics regarding the primary choice of the end-users indicate that an increasing share of the aggregate end-user demand is directed towards the grid-based electricity supply options (Figure 10.4). The first decade of the simulation, a steady increase in the share of the distributed generation is observed. This increase, which can be misinterpreted as an early transition phase, ceases after the first decade, and the share of the distributed generation falls below its initial level of

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Initial price</th>
<th>Price change per year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1.8 Euro/GJ</td>
<td>1.5</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>4.2 Euro/GJ</td>
<td>2</td>
</tr>
<tr>
<td>Biomass</td>
<td>5 Euro/GJ</td>
<td>0</td>
</tr>
<tr>
<td>Uranium</td>
<td>4.5 Euro/MWhe</td>
<td>0</td>
</tr>
</tbody>
</table>

The fuel prices in the base case. Table 10.7.

\[ \text{Figure 10.4. Allocation of end-user demand between central and distributed supply} \]
The factors that lead to this growth-and-decline pattern in the share of the distributed generation, which can also be characterized even as a backlash of a transition towards a decentralized structure, are discussed in the following paragraphs. Figure 10.4 also shows that the grid-based supply prevails as the dominant supply option. Furthermore, most of the demand directed towards the grid-based supply is for the traditional gray electricity. In order to understand the factors leading to this outcome, a closer look at the system is required.

The breakdown of the distributed generation according to the energy source is presented in Figure 10.5, which shows the aggregate situation over all end-user groups. Further breakdown of the distributed generation according to end-user groups can be seen in Figure 10.6. A significant decline in the natural gas-based supply is observed in the figure. One of the underlying causes of such a development is the increase in natural gas prices. The flagship of distributed generation is gas-fired CHP facilities in the Netherlands. However, this option loses its competitive advantage, even considering the benefits from cogeneration, due to high gas prices and discontinuation of former cogeneration support schemes. As a result, only very limited replacement investments are observed against a continuing retirement of the existing CHP capacity. Only for the household users, an insignificant increase in natural gas-based generation is observed, which is due to limited diffusion of micro-CHPs. This constitutes one of the issues related to the decline in the share of the distributed generation in the system.

An important increase in the amount of electricity generated via green options, especially via biomass and wind-based options, is observed during the first half of the simulation. This growth compensates the aforementioned decline in natural gas-based generation, and yields the growth in the share of the distributed generation. The pace of increase stagnates in the second half of the simulation, and even a slight decline in the wind-based generation is observed (see Figure 10.5). Going over the major relations depicted in Figure 10.7, it is easier to understand the factors behind this stagnation. In the growth phase, the SDE support scheme, which supports the green generation via compensating the cost gap between

![Total Distributed Generation by Source](image)

Figure 10.5. End-users’ electricity consumption by energy source (aggregated over all end-user groups)
the grid-based and the green electricity, is the main factor behind the increase. However, SDE makes green options equally cost competitive with grid-based options, but not more profitable than that. Hence, the critical push factor is the extra benefit obtained from green certificates, which fluctuates as a consequence of the balance between green electricity supply and demand. However, the negative feedback loop L1 in the figure pulls the certificate prices down. Observing the demand-supply dynamics for the green electricity presented in Figure 10.8, it is clear that this extra benefit diminishes as a supply surplus situation emerges over time.

One way to neutralize the impact of this negative feedback loop is to support the demand growth. However, in the absence of demand-side support policies (like REB which was abolished in 2004), the green electricity loses its economical appeal for the end-users, and its utilization is confined only to the environmentally friendly end-users. In summary, in the absence of policies like REB, the demand growth stagnates, leading to the dominance of L1 in pulling down the capacity investments. This case constitutes another example of the demand-supply coupling problem already discussed during the experiments with the NavalTrans model.

Apart from this, there is a secondary factor that plays an important role in the stagnation of the growth of wind-based generation: carrying capacity. The surface area where wind turbines can be located, due to both wind availability and environmental concerns, is naturally not infinite for inland projects. Due to significantly lower installation costs, inland turbines are the most profitable wind-based generation option in the model. Hence, in the early phase most of the investments are for inland wind turbines/farms. Increasing costs, due to less favourable locations, for the inland wind turbines is the secondary factor that slows down the growth in wind-based generation. Going back to Figure 10.7, this means that there is a second negative feedback loop that counteracts the growth in the wind turbine installations, i.e. L2.
Finally, PV rooftop panels emerge as an important distributed generation option, especially, for household users. Since the model does not consider surface area issue for PV panels, the extent of the solar-based generation should be evaluated with caution. Despite this caveat regarding the limits of solar-based generation, it is seen that it may establish a position in some market niches.

**Figure 10.7.** Demand-supply interaction for the green generation capacity

**Figure 10.8.** Total green electricity consumption vs. generation
As already discussed in the beginning, end-users’ choices over time indicate a growing load on the central grid, and in the absence of a significant increase in the distributed supply this growth may be even more than expected. The development of the load on central generation system, as well as the evolution of the installed capacity is given in Figure 10.9. A striking observation is a significant over-capacity during the early phases of the simulation. Rather than being a result of endogenous investment behaviour of the model agents, this over-capacity is rooted in the behaviour of the real generation companies. The bulk of generation capacity that is commissioned before 2015 is the set of generation plants already announced by the generation companies and reported by TenneT (2007a; 2008). This covers an approximate total of 8500 MWe generation capacity, for which TenneT has already entered into connection agreement as of 2009, and excludes other announced plans without a connection agreement.

As seen from the figure, the load on the central grid is increasing very slightly, and almost constant in some periods, during the 2010-2015 period. Despite the growth in total electricity demand, only a small portion of this growth is felt on the grid, since the increase in the distributed generation compensates some of that demand increase. However, following the decline in the share of distributed generation, the load on the central grid enters a faster increase phase observed beyond 2020. In short, it is the dynamics on the distributed power generation side that causes the change in the pace of the load growth, rather then the actual growth in the electricity demand.

The aforementioned issue shows a novel complication in the electricity supply system; increasing demand flexibility. This poses a great uncertainty for the generation companies. When the central grid is the only option for the end-users, the key forecast to be made for the capacity investments is about the increase in the demand of the end-users. However, with the increasing number of options for the end-users, additional dimensions are required in the forecasts, such as the end-users’ investments in distributed generation capacity. Although this is not something we directly observe in our simulations, the increasing uncertainty about the demand may lead to risk-averse investment behaviour in the multi-actor liberalized market setup. Eventually, this may cause problems such as insufficient generation capacity in the long run.
The over-capacity situation that is observed in the beginning of the simulation has a set of consequences. Firstly, it causes a decline in the average price of the grid electricity (see Figure 10.10). This is mainly due to upcoming coal-based generators capturing the share of the gas-based generators in the market. A more indirect consequence of the over-capacity situation is the investment barrier it yields. The generators connected to the central grid are high value investments with long lifetimes (e.g. 20-30 years). Due to the value, they constitute important commitments for the generation companies: their likelihood of shifting to alternative generation technologies is very low as long as these commitments exist. Additionally, they are also very likely to demonstrate strong fight-back reflexes against any new entrants through price competition. This means that there is no major possibility of altering the generation park until 2020 since new investments are not promising in such a system state. In other words, any policy intervention during this period will only have impact on the short-run operational decisions, but not that much on the way the generator park evolves. The model agents’ tendency towards not making any capacity investment until the 2020s is a reflection of this problem in the simulation runs.

The investments in the central generation system are dominated by the coal-based options even beyond the initial over-capacity period. Among others, the IGCC plants emerge as a favourable generation option. The consequence of this investment tendencies over time lead to the shift of dominance from natural gas to coal in the Dutch central generation system. Towards the final periods of the simulation run, natural gas-based generators only supply electricity for peak and a portion of the medium load, whereas base load is almost totally supplied by coal-based generators (Figure 10.11). Since there is no significant emission penalty in the base case, CCS is not adopted at all, causing increased emission levels.

This is partially understandable considering the marginal fuel cost advantage over the natural gas-based generators, and the lack of significant carbon emission penalties. However, the coal-based generators typically serve base load. In more practical terms, it makes sense to invest in a coal-based generator only if the generator is expected to be generating electricity with a high utilization level (e.g. 70%). This puts a constraint on the expansion of the coal-
based generators. However, as it is seen in Figure 10.11, this constraint does not seem to be very strong for the Dutch system.

Triggered by this observation from the simulation results, we further investigate the issue, and the character of the Dutch load duration curve (LDC) (more specifically the slope of this curve) is identified to be the main factor in creating such a coal-friendly environment. Figure 10.12 demonstrates two simplified LDCs with different slopes. The areas underneath the curves are equal; i.e. the total energy demand is the same, but the pattern of the demand is different. In these two cases, we consider the situation of a base-load generator that needs to be active at least 67% of the time in a year. The shaded areas represent the part of the total demand that can be served with this particular generator. Clearly, this part gets much larger when the LDC gets less steep. The Dutch LDC, not being a steep one, provides a large room for the coal-based generation, and this explains the extent to which the share of coal-based generation can increase in the simulations.

![Graph of Generation Percentage by Fuel Type](image)

**Figure 10.11.** Share of primary fuels in total central generation

![Diagram of LDC slopes](image)

**Figure 10.12.** Example about the role of the slope of LDC on the share of the base load
The Dutch Electricity System in Transition

Figure 10.13 presents the carbon emission related consequences of the generation portfolio evolution. The emissions increase only slightly during the pre-2020 period. Beyond this point, combined impact of two factors result in a significant growth pace in emissions: first of all the demand on the central grid increases faster; secondly the share of coal-based, i.e. ‘dirty’, generation in the central generation increases during the same period. Hence, significant emission levels are reached in the absence of emission prevention measures, limited diffusion of green generation and no interest towards CCS applications in the base scenario.

b. **Strong regulatory pressure for change**

The results obtained from the base case show that intrinsic processes of the energy system is not likely to lead to a transition when left alone. Such a result should not be surprising. Additionally, the carbon emission levels experienced in the base case seem to be unacceptable within the contemporary European context. Therefore, the second scenario includes a strong regulatory pressure for ‘de-carbonizing’ the system, and investigates the plausible developments within the system triggered by such a pressure.

Currently, the national emission commitments beyond 2012 are not clear, and the ambitions of EU and the member states beyond that time point carries significant uncertainty. In this scenario, it is assumed that the Dutch government, as well as other EU states, pushes harder for emission reduction. This can be conceptualized as allocation of fewer permits, which should eventually lead to increasing permit prices. In initializing the model for this experiment it is assumed that the permit price increases until 2020 reaching 60 €/ton carbon dioxide emitted, and then stays at that level until the end of the time horizon. Although there is no common expectation about the future levels of the permit price, a price above 40 €/ton is evaluated to be a significant penalty.

Different from the base scenario, the share of the distributed generation shows a growth in the final decade of the run in this scenario (Figure 10.14). This late increase is primarily
related to the increasing gray electricity prices: the grid-based supply option loses its cost advantage against the distributed generation (especially against the wind-based generation) due to this price increase. However, this does not explain why there is no change in the early periods despite the significant increase in the prices from the very beginning of the run. An intuitive expectation would be a much earlier increase in the share of the green generation as the carbon permit price increases. The explanation can be found in the way the current sustainable energy support program (SDE) works: SDE does not provide a fixed feed-in tariff for renewable generation, but it provides a dynamic support to compensate the gap between the price of the grid electricity, and the cost of renewable generation. Therefore, as long as the grid-based electricity's price stays below the cost of generation via wind, the wind-based generation will not gain an extra competitive advantage as a result of the increases in the grid electricity prices. In other words, SDE acts like a buffer, and makes the system insensitive to price changes as long as grid-based electricity is cheaper than the distributed generation.

In this scenario experiment, we also observe interesting consequences of the way different policies interact within the current setup of the Dutch system. SDE is a policy scheme that aims to increase the electricity generation via renewable options. The carbon penalties are used in order to steer the system away from carbon-intensive generation methods. At the first glance, these two policies are both against the fossil dependency, and may be expected to have a stronger impact on the system when used simultaneously. However, the simulation experiments do not support such observations. The permit costs are reflected in the cost of generation, and this increases the marginal generation cost of the grid generators. This results in the permit costs being transferred to the end-users; i.e. higher electricity prices. In the same time, due to higher grid electricity prices, the subsidies to be paid by the state to renewable electricity generators decreases: the gap between the marginal generation costs of grid-based and distributed options get narrower. This can be seen in the illustration given in Figure 10.15. As an overall consequence, the tighter carbon permit allocation policy used by the state shifts the burden to end-users. The renewable generation options are supported to the
same level as in the case of the base scenario, total subsidy to be paid by the state is less, and end-users are facing more expensive grid electricity. This can be evaluated as an unintended joint consequence of two separate, but interrelated policy interventions.

Some significant differences are observed with respect to the dynamics of distributed generation (Figure 10.16). First of all, the decline in natural gas-based generation ceases towards the end, and even a slight increase is observed. This can be explained by increasing cost competitiveness of small-scale generators despite the increase in natural gas prices, since they are exempt from carbon payments. Secondly, wind and biomass-based distributed generation follow different trajectories in this scenario. Until 2025 generation costs of the both options are higher compared to the grid-based generation. Therefore they are both supported via SDE. Since SDE provides a subsidy to compensate the difference from the grid-based generation (i.e. options get different levels of subsidy, and their generation costs are made equal with this support), there is no difference between the wind and biomass options. Beyond 2025, average cost of grid-based electricity exceeds the cost of wind-based generation. However, biomass-based generation is still more expensive. This marks the point where wind obtains a financial advantage over both grid-based supply and other distributed generation options. This causes the decoupling of the dynamics related to the biomass and wind-based generation: one experiencing a steep increase, while the other barely sustaining its share in distributed generation.

When the situation for the central supply system is examined, a totally different picture from the base experiment is seen (Figure 10.17). Three periods can be identified for the central supply system. The first one is the pre-2015 period, which resembles the same period from the base case. A decrease in the share of natural gas, and a corresponding increase in the share of coal are observed in this period. Beyond 2015, the impact of the high permit price becomes visible. The natural gas-fired generators having much less emission levels (i.e. almost 50% less per kWh electricity generated) become economically competitive against the coal-fired

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4 Generators with an output capacity below 20 GWh are excluded from the carbon permit market.
generators, and re-gain their share in total generation. This happens through the increase in
the share in load dispatching in the short run, and through the increase in the investments to
gas-based options in the longer run.

Another development is the increase in biomass-based generation. This takes place in the
form of co-firing in central coal-fired plants. Once permit prices exceed a threshold beyond
which emission reduction due to biomass co-firing compensates the extra cost of biomass,
generators start shifting to biomass co-firing. The situation between 2015 and 2025 seems like
cosa is about to disappear from the Dutch system. However, a strong comeback is seen beyond
2025. One important factor in this come back is the increase in the natural gas prices, which
causes the emission advantage to erode against the coal-based generation. The second factor
is the commercial availability of CCS, which eliminates the emission disadvantage of the coal-
fired plants. Such a rapid change in the economic competitiveness of options leads the sharp
shift in the shares of coal and gas in central generation.

The observed changes that are related to the comeback of the coal are very rapid for a capital-
intensive system like the electricity supply. There are a couple of issues that set the scene for
such rapid changes. First of all, both investment and load dispatching processes are driven
predominantly by purely economical concerns. In other words, there is one property of the
options that dominate the decisions of the actors; i.e. the generation cost. However, the nature
of this property is reversible: any development in this property may be reversed in a very
narrow time window. This is exactly what happens in this case. Increasing natural gas prices,
and the introduction of CCS yield a very rapid change in the relative costs of the coal-based
and gas-based options. The dominance of a single reversible property in the actor decisions is
the primary factor behind this comeback.

Secondly, the liberal market structure with multiple actors also enables such a dynamic
behaviour. Since the agents in the model are maximizing their individual profits, they see

Figure 10.16. End-users’ electricity consumption by option
no problem in making investments that will make other agents' investments redundant. This yields to an overcapacity situation where some of the gas-based investments become unprofitable, and practically passive much before completing their lifetimes.

As a result, we observe that if the (desirable) changes in the system are dependent on reversible developments, precautionary measures for ‘anchoring’ these developments may prove useful. For example a progressive carbon permit price that follows the increase in natural gas prices would help to sustain the cost advantage of the gas-based generation. In other words, it would help to anchor the gained advantage. Secondly, rapid changes in the relative situation of the competing options are observed to have the potential to lead to overcapacity situations in multi-actor settings such as the electricity markets.

c. Optimistic technological development scenario
One of the uncertainties about the future of the electricity supply is related to the extent of the technological developments. Some optimistic scenarios claim significant room for development for the green technologies in economic (e.g. investment and operating costs) and operational performance (e.g. efficiency, capacity availability). On the other side, new innovations and technological developments are also expected related to the fossil fuel-based conventional technologies. This scenario explores the impact of such optimistic technological progress: the development limits of the properties of different options are raised, and the widespread introduction of the new technologies (e.g. CSS, SOFC, IGCC) takes place earlier. The modified parameter values corresponding to these changes can be found in Appendix C.

Despite the aforementioned changes, the major behaviour patterns are observed to be very similar to the base case. This behavioural insensitivity is mainly due to the SDE policy, as discussed already in the previous scenario experiment. The economical properties of the distributed generation options are more favourable in this case, but this development is not likely to make them cheaper than the grid-based supply. As long as this is the case, the changes
in the economical properties of the options only change to subsidies to be paid by the state (i.e. generation costs are lower, and the gap to be compensated by the subsidy is less), but fail to provide the extra push to initiate a system-wide transition.

The share of the grid-based generation, as well as the composition of the capacity connected to the central grid is almost identical to the base case. Slight changes are observed regarding the composition of the distributed generation: first of all there is some increase in the domestic green electricity generation, despite the absence of an increase in the demand for green electricity (Figure 10.18). This is mainly triggered by the slight increase in the economic viability of the biomass-based options. When the situation of the end-users is studies, it is

![Green Electricity](image1)

**Figure 10.18.** Demand vs. supply of green electricity

![Total Distributed Generation by Source](image2)

**Figure 10.19.** End-users’ electricity consumption by option vs. supply of green electricity
observed that PV panels and m-CHPs obtain a higher share in the supply portfolio for the household-type end-users. However, the impact of this is a negligible development when the aggregate situation over all end-user groups is considered (Figure 10.19).

This scenario experiment reveals the behavioural insensitivity of the Dutch electricity supply system to technological uncertainty under the current SDE support scheme. Naturally the insensitivity mentioned here is within the time horizon of the runs. The delays in the development of the generation options, and their active utilization (adoption, investment, etc.) create a sort of systemic inertia. In the presence of such inertia, it is difficult to observe significant changes in the system even under optimistic condition.

Before proceeding, it should be noted that the exploring the technological uncertainty demands much more than just considering optimistic development trajectories for some options, as we do in this experiment. This experiment is conducted just to explore if any of the currently available novel options will stand out in case it develops beyond the common expectations.

d. ‘Greening end-users’ scenario

The final scenario to be discussed in this chapter is related to the plausible changes in the electricity supply system due to significant changes in the preferences of the end-users. Since the end-users, and more specifically their behavioural identities, are explicitly represented in the ElectTrans model as a vital aspect of the socio-technical system, the model allows us to conduct such experiments.

As already mentioned, the different end-user groups are characterized according to the scale of their electricity demand, and their preferences that guide these users in their supply choices. In this scenario, the priority of the environmental issues experience significant increases for all actor groups. In a way, the environmental concerns gain some priority for all actors in comparison to the purely economical concerns. In line with this, a steady ‘greening’ takes place among the household-type users during the simulation run: the environmental friendliness becomes the primary criteria for supply choices by the end of the time horizon. A similar development takes place for the agricultural and commercial end-users. They go through a slower preference shift, and environmental friendliness becomes equally important with economical ones. Industrial users also experience some level of ‘greening’, but the economical aspects still dominate their choices through out the time horizon of the analysis.

The changes in the end-users’ preferences trigger a demand formation for the green electricity. Being the readily accessible and most cost-competitive one, the grid-based green electricity attracts most of this newly forming demand. As seen in Figure 10.20 the demand for green electricity makes a steeper climb compared to the base scenario. As a consequence of higher levels of green electricity demand, the supply surplus diminishes towards the end of the time horizon, which increases the green certificate prices. This latter increase provides an incentive for further investment and green capacity, hence the green generation, continues to grow throughout the time horizon, rather than stagnating, as it was the case in the base scenario. This observation also supports our previous conclusions in the base case regarding the interplay of the demand and supply of green electricity.
The early supply surplus and the intrinsic investment delays create some level of inertia within the system. As a result, the impacts of the preference changes that start around 2015 on the green generation dynamics are only felt beyond 2025. The aforementioned increase in the green certificate prices provides an extra push for green distributed generation options. This keeps the share of the distributed generation at higher levels compared to the base scenario. Although it is not possible to talk about a notable increase, the share of distributed generation sustains the 40%-level (Figure 10.21).

As seen in Figure 10.22, the biomass-based generation experiences a steady increase, while the wind-based generation stagnates following an early rapid growth. Being an initially more attractive option, wind-based generation demonstrates an earlier growth. However, once the
favourable inland spots are used, the cost of capacity expansion gets less attractive for the wind farm installations. This can be considered as a consequence of the capacity crowding dynamics, where the favourable spots for the inland wind farms constitute a natural capacity limit beyond which the options starts losing its economical attractiveness. As a result, as the limits of land-based wind installations are approached, biomass captures the economic advantage and attracts most of the demand for green electricity generation. This indicates that being an option that has the potential to experience an early take-off, the wind-based generation may be unable to sustain this growth unless the technological developments close the gap between the already favourable inland and other wind farm installations in economical terms.
The shift of demand to green distributed supply options results in a slightly less load on the central generation plants compared to the base scenario. This slight decrease does not have a major impact, and the dynamics regarding the central generation are pretty similar to the base case. When the overall system is investigated, the dependency of the system on conventional fossil fuels is intact (Figure 10.23). The shares of energy sources, except biomass, have very similar dynamics with the ones observed in the base case. As briefly discussed above, the extra demand for the green options triggered by the general greening trend among end-users yield an increased share for biomass-based electricity generation in the Dutch context. This indicates a very strong internal inertia in the system that is hard to overcome just by changes in the end-user preferences. At least, a change at the scale that is considered in this experiment only has a marginal impact on the system.

10.4. Benchmarking the modelling study

As is the case in the previous two modelling studies based on the actor-option framework, we aim to investigate the extent to which the developed models are conceptually rich enough. In the previous two cases, this has been done by checking the extent to which the model incorporates the key processes highlighted in the historical case study. Since this modelling study is not based on a historical case study, the same cannot be done here. As an alternative approach, we benchmark the developed model, i.e. ElectTrans, with other models of the Dutch electricity system that have been developed with somehow similar objectives. This way we aim to identify the limitations of the model, and also its merits in terms of its conceptual coverage.

One of the rare studies focusing on non-technical aspects of the system has been conducted by de Vries (2004). The study focuses on generation adequacy and capacity expansion in liberalized markets. Among other things, it involves a detailed qualitative analysis of the institutional setting of the Dutch system, and is supplemented with a very simple model that is used to demonstrate the probable investment tendencies over time. de Vries aims to understand the possible dynamics under different capacity mechanisms, such as capacity payments and energy-only markets. Although de Vries aims to develop a loose link with the Dutch market via initializing the model to match the Dutch case, the model is primarily used to understand consequences of differing market designs, rather than to develop a better understanding specifically about the Dutch electricity market.

An important model in the Dutch energy policy is POWERS. POWERS is a national-scale energy model developed in 2001 as an ECN project (Seebregts et al. 2005). The primary aim of the model is to provide forecasts regarding electricity prices in the liberalized Dutch electricity markets. The model is developed mainly using system dynamics tools, and is coupled with an optimization model. The model is extensively used to develop the long-term projections (up to 2020 and 2040) published by ECN, and also serves as an important support tool in national energy policies. The model incorporates a very detailed depiction of the Dutch supply system at the level of individual generation plants, and interconnectors with the neighbouring EU countries (i.e. UK, Germany, France, Belgium, and Norway). As mentioned earlier the primary aim of the model is to generate projections regarding electricity prices in the wholesale market. While doing so, the model also generates projections regarding the production mix, import/export balance, and overall CO₂ emissions. The model does not incorporate an endogenous capacity investment structure. Hence, during the course of a typical run (i.e. 30
years horizon), either investment decisions over time are given as a pre-determined input at time 0, or input to the model during the course of the run by the user by intervening in the run. In the latter case, new investment decisions are given using a 'back-of-the-envelope' style calculation (Seebregts 2009, personal communication). Despite the extensive technical resolution of POWERS, social components of the system, e.g. investment and operational decisions of actors and interaction of these decisions, are left out as a design decision.

The PhD thesis of Rödel (2008), as it focuses on technology and infrastructure, stands as another example of holistic studies of Dutch electricity system with a purely technical point of view. The dissertation provides an extensive review of power generation technologies at a detailed level. Additionally, a good snapshot of the Dutch supply system as it is in 2008 is provided. Although one of the objectives of the research is to study future projections regarding the environmental performance and the security of supply, what is provided in the dissertation in terms of future dynamics of the system is quite limited. An optimization model is run for two discrete points in time, i.e. 2010 and 2025, to determine optimal investment decisions at those points from the perspective of a planner looking at the whole system. The generator park is assumed to be fixed between these time points, and the model calculates electricity generation related figures, such as total electricity output and CO₂ emissions, over time with this fixed generation system. In short, the study does not focus on the role of non-equilibrium dynamics of the system until those discrete points in time.

Voorspools' PhD dissertation (2004) focusing on the Belgian electricity system constitutes another relevant study. The model developed for this research is rich in detail both in the way generation technologies and facilities are represented, and in the time resolution about demand-supply balancing (e.g. demand is represented at the hour-level). The main objective of the model is to study unit commitment and dispatching in a multi-region system with storage for a 1-year time horizon. The model takes the power system structure and demand as input, and the output consists of the power generation, and related emissions and fuel usage for each individual plant. Contrasting with the work reported in this chapter, Voorspools' work does not intend to study either long-term capacity evolution dynamics, or actor (i.e. generation companies, end-users) behaviour over time. Therefore, they are excluded from the model.

The third of PhD research cited in this chapter was conducted by Benders (1996). This study is composed of developing two distinct models; MEED (for Model to Evaluate Electricity Demand) and PowerPlan. MEED is developed more for scenario studies, and designed to study demand dynamics mainly. On the other hand PowerPlan is developed as an interactive game regarding the supply side development of the system. Being designed as an interactive game, PowerPlan 'outsources' actor decisions on capacity investment to the players. The model, which constitutes the basis for the game, is all about load dispatching and evaluation of the overall performance of the system in satisfying the demand given in the form of a load-duration curve (LDC). In that sense, the work seems to be more focused on how the system functions in its current state, rather than how it changes over time from its current state. Furthermore, the model was developed in the centralized control era before liberalization during which the operation of the system was being managed in a significantly different way. Therefore, this study is not a very good benchmark with respect to the key issues that need to be covered in representing the electricity system.
Chappin and Dijkema (2009) also utilize holistic simulation models in exploring possible trajectories in the Dutch electricity system. Among relevant work reported in this section, their work shows the highest proximity to this study regarding conceptualization of the way overall system works (e.g. depiction of multiple generation companies as independent actors). However, they diverge in the objectives and also in the boundaries of the study. The primary objective of the Chappin and Dijkema’s work is to compare the impact of two policy measures specifically aiming reduction in emissions from electricity generation. In doing so, they examine emission levels as well as average market prices to compare the impact of different policy schemes. Issues like green distributed generation, green electricity markets are not explicitly covered in the model, but emphasis is kept on central generation. In other words, the end-users of the electricity are kept out of the system boundaries of the model, and the load on the central grid is treated as an exogenous variable. Being the core issue in their study, the carbon permit market occupies the central spot in the conceptualization.

An initiative worth mentioning is the Energy Transition Model (ETM) developed by a consortium, which consists of Delta, Eneco, Enexis, Essent, GasTerra, Logica, Shell and the Municipality of Amsterdam, lead by Quintel Strategic Consulting (2009) model is designed to support ‘interactive scenario planning’ processes and is an interactive flight-simulator in some sense. The model provides the consequences of several decisions and assumptions (e.g. fuel prices, increase in demand, new generation facilities to be invested) provided by the user about the energy situation in 2040. Simply it can be categorized as a complex static calculator that captures the complicated relationships of decisions and consequences within the energy context, rather than a dynamic simulator.

The scope of the aforementioned modelling studies and the contents of the corresponding models constitute a benchmark against which we can reflect on the ElectTrans model in terms of its coverage. When we consider ElectTrans and the other models mentioned above, the primary source of the differences stem from the main objectives for which these models are developed. Although all key processes encountered in these models are represented also in ElectTrans, some of these them are depicted in simpler forms. For example, the maintenance scheduling of the central generation plants, which is optimized in Rödel’s work, is not represented in detail in ElectTrans, but the long-term impact of such maintenance activity is considered as a percentage loss in their operational uptime. The load dispatching is conducted for 15-min intervals in Voorspool’s work. Considering the time scope of a transitional change, ElectTrans works at a higher time-scale; hence, load dispatching is not simulated in this time precision. However, ElectTrans incorporates a heuristic that converges to the average long-term consequences of such fine-grained dispatching, and this serves the purposes of our study. Chappin and Dijkema explicitly model the carbon permit market where the demand and supply sides interact and determine the resulting prices. The permit price is included as an exogenous variable in ElectTrans. In doing so, we consider that the carbon market is a EU-wide market where the sinks and sources for the permits are much greater than the Dutch national electricity market in scale. Therefore, we assume that the evolution of the price is mainly dependent on the developments beyond the Dutch electricity market, and include such developments as exogenous scenarios. As a result, we concluded that the coverage of the ElectTrans model is satisfactory in representing the internal functioning of the electricity supply system. Although there are some simplified or omitted processes, it is not due to the limitations of the framework, but due to intentional modelling choices and assumptions.
There is also a set of aspects of ElectTrans that provides advantage in the context of studying transition dynamics. As a starting point, the electricity transition is defined as a significant change in the way need for electric power is fulfilled. A direct consequence of such a definition is a wider system boundary compared to most of these studies. The boundary utilized in developing ElectTrans covers end-users and distributed generation besides the central electricity generation system. This way, for example, the possibility of the end-user demand triggering a distributed generation growth is covered in the model, rather than taking this demand being satisfied via central generation for granted. Additionally, the behavioural dimension of transitions is considered explicitly and in more depth in ElectTrans, since the decisions/actions of system actors (e.g. end-users’ demand allocation among available options, generation companies’ investment choices) are seen as the main driver of change. Technical and infrastructural drivers are supplemented with social drivers in ElectTrans.

10.5. Conclusions from the modelling study
The modelling study on the Dutch electricity system is the last of the three modelling studies we have conducted to explore the applicability of the actor-option framework, and to investigate the limitations of the framework. The electricity supply context has been chosen deliberately, since we aimed to use the framework in modelling a large-scale socio-technical system with a complicated techno-physical and institutional structure. Moreover, the electricity supply case is not a historical transition as is the case with the other two modelling studies. We consider the case as an ongoing transition, and we aim to demonstrate the type of insights that can be developed about the plausible behaviours of the system during this process using the proposed simulation-supported approach.

One of the main objectives, as stated above, in this study is to investigate the conceptual and practical limitations of the framework in representing the complicated structure of the electricity supply system. In the historical cases, the conceptual sufficiency of the framework has been evaluated as we investigate whether the concepts introduced in the framework are sufficient to represent processes that are claimed to be important in the case studies in their ex-post analyses. Since the electricity supply case is not a historical transition, we lack such a reference point for investigating the conceptual sufficiency of the framework. As an alternative way to go, we investigated a set of models developed about the Dutch electricity supply system in order to identify the key issues and processes that are included in these representations (Section 10.5). These models provide a benchmark for us for evaluating the sufficiency of the conceptual coverage of the framework; can we model these key issues and process using the conceptual language provided by the framework? Compared to most of the considered models, ElectTrans operates at a longer time horizon. In that respect, a set of operational processes (e.g. load dispatching, maintenance scheduling, carbon pricing) is represented in less detail in the model. However, such simplified representations are a consequence of the deliberate assumptions made, and not due to some conceptual limitation of the framework. Besides, considering the system boundaries employed, it is seen that the system boundary of ElectTrans guided by the actor-option framework is more comprehensive than these former electricity system models. As a result, we did not come across any major conceptual limitations posed by the actor-option framework in modelling the complicated structure of the electricity supply system.
On the practical side, a set of issues appears to have the potential to pose problems especially during the analysis process. The complicated internal structure of the system makes a very aggregate representation of the system difficult to validate: it is hard to deduce if there is an aggregate regularity/process that represents the conjoint outcome of detailed internal processes like load dispatching and unit commitment, for example. As the system boundaries are wide, this results in a model with a fairly large number of variables. Considering the time horizon, and possible technological and social contingencies, the space of uncertainties is also very large. In the presence of a large number of variables, and high uncertainty with some of these variables, the experimentation becomes a demanding task. Relying on a limited set of experiments may lead to conclusions that are not robust on the one hand, and going for a full scale exploration of the parameter uncertainties and scenarios demands a great number of simulation on the other hand. In that respect, systematic approaches for conducting large number of experiments, and also for analyzing the resulting large number of model outputs are required to foster the applicability of such large models.

Related to the aforementioned problem, a proper analysis of the transition trajectories for the Dutch system should rely on a great number of experiments, and in-depth analysis of the resultant behaviour patterns. Since our primary aim is demonstrating the applicability and investigating the limitations of the framework, the set of experiments reported in this chapter are very limited for such an ambition. However, even this limited set of experiments reveal some interesting points about the behavioural tendencies of the Dutch electricity system, and their underlying structural causes.

ElectTrans is an empirically grounded model, which is rich in detail, and it corresponds to the contemporary situation of the Dutch electricity system. Considering the insights developed during the simulation experiments, the purpose ElectTrans serves is case-specific insight development. From the way we utilize the model, and the discussions on the model output, it should be clear that this purpose does not include making any specific forecasts about the future state of the system, or the penetration level of a specific technology. As Myrdal puts it, we primarily aim “to analyze the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its internal processes” (Myrdal 1957, pg. 18). What can be the conjoint system-level outcome of a set of simple internal processes if a particular policy is changed? What makes it difficult to move the system away from the fossil fuels? It is this kind of questions we aim to answer in the specific context of the Dutch system by using the ElectTrans model.

The abstraction level used in developing the ElectTrans model makes it possible to analyze the interaction of specific policy measures in the context of the electricity supply system. The simulation experiments and further investigation of the system structure lead to a set of insights related to the system-level implications of certain policy measures. One of such insights relates to the growth of the renewable generation capacity in the system. The SDE policy scheme is a supply-side support program that aims to eliminate the economical disadvantages of the renewable generation options, and foster expansion in the generation capacity. However, the elimination of the disadvantage is observed to have a limited impact, and an additional push that provides extra benefits is required. The green certificate payments provide this extra push in the model. If the demand fails to grow, it is seen that this extra advantage diminishes over time due to an emerging renewable generation surplus. Eventually, the growth in renewable generation capacity stagnates. This observation highlights the
possibility that a capacity growth in the early phases of the application of the SDE scheme may be dependent on other factors in the system (e.g. an existing renewable generation shortage), and it may be misleading to attribute the success solely to the SDE scheme. This success may be a short-lived one. Unless the SDE policy scheme is coupled with a demand-side policy such as the abolished REB, it is possible that the renewable generation options may experience only a limited penetration level. This observation also relates to the impact of conjoint demand-supply dynamics on the penetration level of a promising option analyzed with the NavalTrans model at a general level (Section 9.3).

Another observation is about the coal-friendly nature of the Dutch system. Both in the base run, and in other experiments the coal-based options seem to dominate the system, or to have a very strong comeback potential. One case-specific factor is identified to be the character of the Dutch load pattern, which enables a large portion of the demand to be serviced by the base-load generators. Another factor is as a more general issue that can also be observed in other socio-technical contexts. The decisions of the system actors are dominated by a single criterion (i.e. economical profitability), which develops in a reversible manner: any development can be reversed easily and quickly. When this is the case, this creates a scene that makes it likely to observe sudden shifts in the ‘favourite’ options, and sudden comebacks in the system. As discussed in Section 10.4, this can be seen as a structural vulnerability of the electricity supply system, especially in the multi-actor liberal setting of the market.

A concrete benefit of using a policy-level abstraction level is observed in analyzing the plausible impact of the carbon permit policies on the system behaviour. The carbon pricing policy broadly aims at de-carbonizing the electricity generation. The SDE policy scheme, as already mentioned, aims to foster the growth in the renewable electricity generation. At this general level, both policies are expected to push the system away from the conventional fossil fuel-based options, and towards the cleaner or green options. Since having somehow similar goals, the joint application of these two policies may be expected to yield better results compared to applying them in isolation. However, when their joint impact is analyzed at a detailed level, our observations are somehow different. Due to the way the SDE support mechanism works, introducing higher carbon penalties does not bring about an extra push in the system. However, it leads to the shifting of the financial burden of the SDE support scheme to the end-users through increasing the price of the grid electricity. As result, the joint application of these two policies may lead to no synergetic impact on de-carbonization, but to less financial burden for the state and more for the end-users.

Finally, the endogenous representation of the end-users help to explicitly observe a novel development for the electricity generation: increasing demand flexibility. Since the end-users also have the option of using distributed generation options, they are no longer confined to the central grid anymore. Therefore, the demand is no longer insensitive to changes in the grid electricity, and can shift to alternatives. This leads to the fact that the changes in the end-user demand and the changes in the load on the central grid can be decoupled, as we clearly observe in some of our simulation experiments. Such a development increases the demand uncertainty for the generation companies, and may have an important impact on their investment behaviours. Although we do not explore this issue in the presented set of experiments, the consequences of increasing demand uncertainty on the overall over/under capacity situation of the system appears as an issue that deserves further investigation.
Reflections Based on the Modelling Studies

11.1. Introduction
The chapters in this part of the dissertation present three modelling studies that are based on the actor-option framework. Each of these studies puts forward insights and conclusions about the historical and/or plausible dynamics that are specific to the transition case analyzed. However, the primary objective of conducting these three modelling studies is not confined to gathering some case-specific insights. As already discussed in the introduction section of Part III, we aim to explore the extent to which the actor-option framework serves as a general conceptual basis for simulation-supported analyses of transition dynamics. In addition, we also look for specific circumstances that support the relevance of the basic premises of the actor-option framework. In this section, we reflect on these three modelling studies, and discuss general points regarding the actor-option framework rather than the issues related to the particular cases analyzed.

11.2. On the basic premises of the framework
As a result of our preliminary investigation on transition processes, and how they can be studied, we recognize three conceptual issues as important to address for enhancing the conceptual foundations of the transition studies field. These issues are discussed in detail in Section 1.4. As a result, we make the following premises in developing the actor-option framework:

- Social actors’ behaviours are key to understanding transition dynamics, and should be an explicit part of explanatory models (Actor representation premise)
- Components of a socio-technical system that have different character in terms of the ways they change over time should not be aggregated in the conceptual models that aim to explain the unfolding of a transition process (Disaggregation premise)
- The conceptual models should reside at an abstraction level that allows direct correspondence with real-life policy measures (Policy-relevant abstraction premise)
In Section 1.4, we discuss the logical reasons behind these premises. One of the purposes in conducting the experimental modelling studies is to identify circumstances that support these premises, and stand as evidence for the added value of the premises.

In several cases, we observe that the differences among the social actors in the system play an important role in shaping the way a transition unfolds, which supports the disaggregation-related premise of the framework. For example, in the waste transition case, a domino effect that propagates along the different actor groups is observed; changing public opinion influences the regulator’s actions, which later lead to the changes in the decisions of the providers and the practitioners. This inter-actor propagation is identified as a source of the inertia in the system while steering away from the incineration option. The recognition of this inter-actor influence is crucial in explaining the observed dynamics.

The naval transportation case also provides evidence regarding the importance of the differences between, and also within the actor types. The actions of the providers and the practitioners have very different impacts on the way the system evolves. Especially, in one of the scenario experiments (i.e. the ‘capacity sensitive demand-side’ scenario in Section 9.3.b), it is seen that the separate analysis of the behaviours of these two actor groups is crucial in order to understand the observed dynamics. In the circumstances depicted by the scenario, the increasing demand for the new technology eventually leads to the stagnation of the penetration of new technologies in the system due to capacity crowding (i.e. overloading of the system with a demand that cannot be handled properly with the existing capacity). The demand increase first supports the option’s development, and later brings about its limited penetration in the system. In a sense, there is a non-linear relation between the practitioners’ interest in the option, and the option’s success in the system. When we analyze the model structure, we see that this non-linear relation is the result of two simple feedback processes, one being related to the capacity crowding driven by the practitioners, and the other being related to the capacity development driven by the providers. Both processes are easy to identify and formulate, if the provider and the practitioner sides are represented separately in the modelling process. However, the formulation of such a non-linear process is likely to be difficult, or even overlooked when the provider and the practitioner sides are aggregated into a higher-level construct. A very similar circumstance where it is important to disaggregate the actor roles is also observed in the electricity supply case: the stagnation of the growth in the green generation capacity despite ongoing government support in that direction can be explained by referring to the dynamics on the demand side. In cases where the demand-supply dynamics are not considered separately, it is difficult to explain the weakening of the impact of the support programs (e.g. SDE) following their early success.

As a result, we observe that it is the interplay of the changes in the regulatory, provisional and demand-side aspects that explain the observed dynamics in all three cases. While identifying and formulating the processes related to each of these aspects is not very challenging, doing the same for an aggregate process that represents the conjoint result of the developments in these different domains would be much harder. For example, it is easier to formalize the increase in the practitioners’ interest, or the change in the capacity investments as a response to changing economical conditions. However, directly formalizing how much power a regime gains or loses due to such condition changes (which is expected to be a conjoint result of the changes at the actor level) is much more challenging. In that respect, separate consideration...
of these dynamics proves to be valuable in both formalizing the model structure, and also in analyzing the model output.

Furthermore, the importance of capturing the heterogeneity within the practitioner group is clearly observed both in the naval transportation, and the electricity supply cases. In both cases, a subset of the practitioner group serves as a nurturing space for the novel options; i.e. postal services for the steam-ships in the NavalTrans case, and green households for the green electricity in the ElectTrans case. The roles of these outlier social groups are clear in the observed dynamics, and the impact of such groups may be overlooked when the differences among the social actors of the same type are averaged out for aggregation.

During our modelling experiments, we also observed that utilizing an operational and policy-relevant abstraction level has an important added value during scenario and policy experiments. In the experiments we have conducted with the NavalTrans model, we explored the consequences of the actors’ sensitivity to capacity shortages. Since the model resides at the abstraction level of the operational level components of the system, the implementation of such an extension was a fairly simple task. We did not have the need of translating this kind of behaviour to a higher abstraction level, and try to deduce what kind of a change this would mean in terms of these higher abstraction level elements. This ease of extending the model also relates to the explicit representation of the actors in the model. The added value of using this abstraction level becomes much more clear when the socio-technical system's internal functioning is quite complicated, as the Dutch electricity supply system. The ‘regime’ in the considered case can be characterized as the fossil fuel-based central supply system. If we aim to treat this system as a sort of emergent entity, it is extremely challenging to deduce its behaviour due to the level of complication in the way this system operates. For example, even simple changes in the load dispatching regulations may yield significant changes in the emission performance, as well as the cost of electricity without any major changes in the techno-physical configuration of the system, or in the behaviours of the social actors. However, it is not very easy to formulate such changes in the emergent entity interpretation, unless the internal functioning of the system is represented explicitly. The same holds for analyzing the impact of the policies on the behaviour of the regime. Our experiments show that two transition-favouring policy interventions are actually interacting due to way the market is organized. The resulting impact on the regime is difficult to foresee, unless we know, in detail, how the system actually works. In other words, in order to analyze the impact of such policies from the realm of policy makers, it looks like opening the regime box, and depicting the internal functioning of this entity at the abstraction level of the policies is crucial. For example, the insensitivity of the system to increasing carbon prices, or the stagnation of the green electricity generation capacity following the shift from the REB to the SDE policy scheme would also be difficult to foresee. Similarly, understanding the system-wide consequences of these policy changes would be hard without analyzing the impact of these policy changes on the operational level.

11.3. On the level of generality of the framework
The actor-option framework is proposed as a general conceptual framework that can be used in different socio-technical contexts. The cases that are used in the modelling exercises are deliberately chosen from different contexts in order to explore the extent to which the
framework can live up to this *generality* claim. The general applicability of the two fundamental components of the framework is important in this context. Regarding the actors, and the actor roles, we did not encounter any conceptual misfit, and the roles are observed to be valid in all these three cases. We also observe that these four roles need not exist in each case, as the analysis on the naval transportation is based only on the two of these four actor roles. Besides, the option concept, as it is defined in the framework, can successfully be used to represent a variety of things such as technological artefacts (e.g. micro CHP units), processes (e.g. landfilling) and services (e.g. shipping services). An equally important issue is related to the applicability of the general mechanisms of the framework in different contexts. Based on the three modelling exercises, we see that the key developments taking place in these transitional change processes can be classified as specific instances of the general mechanisms in the framework. In other words, we were able to represent the ongoing processes that drive the studied transitional changes in terms of the general mechanisms of the actor-option framework.

Besides the contextual generality, we also demonstrate that the framework is general in the sense that it can support the development of models with different aggregation levels, and also the development of models for transitions with very different characteristics. Among the three models developed, *WasteTrans* has the highest aggregation level: a single provider actor (in the model) represents the aggregate of all the waste processing companies, and the installed capacity of a single incineration option represents the aggregate of all the individual incineration facilities in the actual system. On the other hand, the model developed for the electricity supply case is the most fine-grained one. Each power generation facility is represented separately, each provider agent in the model corresponds to a single electricity generation company, and a range of detailed technologies is covered as options rather than using an average ‘natural gas-based generator’ option, for example. This demonstrates that the concepts and the mechanisms of the actor-option framework allow the analyst to work at different aggregation levels depending on the requirements of the specific transition case being considered.

Moreover, the modelling studies also show that the models developed with the framework can be used to analyze transitions with differing characteristics, and to investigate different aspects of the socio-technical system. Among the cases considered, the naval transportation case has a technology-centred character, and the transition is driven mainly by a set of mechanisms that are related to the techno-physical aspects of the socio-technical system. The waste management case, however, is mainly driven by processes related to the environmental damage caused by the socio-technical system’s functioning, and the changes in the social actors’ priorities that follow this damage. In the electricity supply case, the aspects that we are able to experiment with are social (e.g. norms, preferences), regulatory (e.g. market regulations, support schemes), and also technological (e.g. new technologies).

### 11.4. On the conceptual and practical limitations

In addition to exploring the extent to which the framework has a general character, we also investigated the *conceptual* and *practical limitations* of the framework. The *conceptual limitations* are related to the difficulties encountered in representing particular issues and processes from the actual transition context using the conceptual elements of the framework. The most important conceptual limitation of the framework is related to the representation
of the institutional change processes endogenously. The mechanisms of the actor-option framework do not cover the processes according to which formal and informal institutions develop. Some of the mechanisms may be appropriate to explain the changes in certain aspects of institutions, but we have not conducted an in-depth analysis regarding this point. While not ignoring the role of institutional changes in a transition process, the actor-option framework does not include a set of mechanisms sufficient to explain such changes. This limitation has been overcome in different ways depending on the situation. In the waste transition case, a proxy variable, i.e., regulatory support, has been used to represent the development of the formal institutions favouring a certain option. Despite being an abstract and very general concept, it served the purpose very well in that case as an indicator for the direction of change in the system. In the electricity supply case, the changes in the formal institutions are included as scenarios into the analyses. Changes in the informal institutions such as social behavioural routines, can also be considered in this way.

Another point that may be considered as a limitation is about the way sudden changes such as crises, internal shocks, or accidents are dealt with. The framework does not specify any mechanism that explains the sudden appearance of such events, and in the models these events are integrated in the form of exogenous shocks to the model. Sometimes these sudden events are rooted beyond the boundaries of the socio-technical system, and their representation as external shocks is appropriate. However, some of these sudden events are clearly related to the internal functioning of the system, such as the unexpected closure decision regarding a particular landfilling site in the waste management case. The framework can be improved to account for such internal shocks, which may prove to provide deeper insights than incorporating these sudden events into the models as external shocks.

The practical limitations correspond to the difficulties in representing the concepts of the framework in quantitative simulation models, which demands quantification of the concepts and formalization of the mechanisms. The most challenging issue here is related to the mechanisms that are about the behavioural identity of the actors. In other words, the mechanisms related to the preferences, references and commitments of the actors. Although the direction, triggers, and drivers of change are easier to identify, it is difficult to quantify the pace of change in these issues. Similarly, the initialization of these social aspects is also a serious quantification problem. They are generally difficult, if not impossible, to measure, and it is possible to quantify them in numerous ways that would be consistent with the qualitative information possessed regarding these aspects. This problem is common to all modelling efforts on social issues. As a way to address the problem, we rely on extensive sensitivity analyses in order to investigate the robustness of the results under different initializations of the social aspects (e.g. preferences), and formalizations of the corresponding mechanisms (e.g. preference change). We demonstrate a set of examples of such sensitivity analyses in the waste management case. However, as the number of soft variables in the model grows, a conventional sensitivity analysis may not be sufficient for the task, and advanced experimentation approaches may be needed to supplement large models developed with the actor-option framework, such as ElectTrans.

Another problem, which also demands advanced experimentation approaches, is related to the social and technological uncertainty confined in the boundaries of a model developed with the actor option framework. The framework may be used to develop models that cover
a wide range of aspects (e.g. social, regulatory, technological), and models that are not very aggregated. The ElectTrans model developed for the electricity supply case can be considered as an example of such a model. A model that carries these properties also incorporates a great number of variables with high uncertainty. In order to make robust conclusions with such models, a limited set of simulation runs would not suffice; an extensive exploration is required. This is observed as a serious practical issue regarding the utilization of the framework, and we recognize the need to couple the framework with structured exploratory experimentation approaches in order to address such a practical problem.

11.5. On the potential uses of the developed models

In Section 2.3 of the dissertation, we discuss three different purposes for which simulation models can be utilized in transition studies. In this section, we investigate the correspondence between the ways we used the models in the modelling exercises, and the aforementioned three model-use schemes.

None of the modelling studies discussed in this dissertation purely aims for theory testing and development. Hence, we do not provide a proper example for using a simulation model for theory testing and development purposes. However, the waste transition and the naval transportation cases carry the important characteristics of such a model-use. The models in these cases are developed based on the accounts provided by the original authors who have conducted the case studies. In these case studies, the authors describe/explain the way the corresponding transition took place. These explanations can be considered as the authors’ dynamic hypotheses related to the observed transitions. By building the models based on these explanations, we actually test these hypotheses. First of all, it enables us to check whether there are inconsistencies, or important voids in the verbal explanation of the original authors. Secondly, we test whether the models can actually replicate the historical transition trajectories, or not. While the models’ successes in replicating the dynamics can be considered as a supporting evidence for the viability of the provided explanation, a failure to replicate the dynamics would constitute very strong evidence about the insufficiency of it. In both cases, it is observed that the developments and the relationships discussed in these case studies are actually capable of yielding the historical dynamics. In other words, the accounts in the case studies are supported by the dynamic evidences generated by the models.

The naval transportation case provides examples of model use for generic insight development. The base version of the model, i.e. NavalTrans, is developed based on the case study, and corresponds to the specific case reported in the case study. However, during the experimentation phase, we loosen the connection of the model with the actual case of the British naval transportation system, and start using it as a general depiction of a socio-technical system. During the experiments on capacity sensitive demand-side, we aim to develop general understanding about the interplay of demand and capacity in a system where the societal function is heavily dependent on the service capacity (i.e. vessels available). The experiments with the sub-groups of the demand-side actors aim to understand the role of the preference distribution of the actors on the development and diffusion of a novelty that depends on scale of utilization for improvement. In this latter set of experiments, we observe a transition pattern (i.e. terraced transition) that is mainly shaped by the preference distribution of the users. This is an example of how simulation models can be used in this mode to identify
Reflections Based on the Modelling Studies

11.6. On the relevance of having a general explanatory framework

We discuss the issues that constitute our main motivation in conducting this study in Chapter I and in Part II of the dissertation, in detail. Broadly, the motivation can be summarized by two ideas; there is a need for using explanatory models for analyzing transitions, and it is beneficial to have a general conceptual framework for developing such models. The relevance of both ideas may be intuitive and would go without saying for some scholars. It is still beneficial to reflect on the relevance of these two ideas based on our observations in the three modelling exercises discussed in Part III.

The added value of an explanatory model can be seen when we consider the insights that can be developed with such a model in contrast with what can be provided with a detailed descriptive account of the system and the transition process. Knowing the phases through which the system went through is very valuable. However, if we aim to develop an understanding about the transitions and socio-technical systems, we need to focus on the processes through which the system moved from a certain phase to the next one. In a simplified depiction, an explanatory model is composed of the processes that connect the dots presented in a descriptive narrative. Once such a model can be developed, it enables us to go beyond the specific transition narrative, and to elaborate on possible alternative trajectories of change.

The experiments we have conducted with the NavalTrans model can be seen as concrete examples of such an added value. Being able to replicate the dynamics in the transition narratives, the model stands as a candidate explanation for the transition process. After this point, the model structure enables conducting “what if…?” type of analyses, which not only tells something about the specific transition observed, but also about what could have
happened in such a socio-technical system under different circumstances. The experiments with the actor heterogeneity, where we observe the terraced transition pattern, would not be possible, if the model was not an explanatory one in nature. The situation is much more evident in case of the ElectTrans model. We aim to understand how the system may react to certain interventions. In order to do this, we need a simplified representation of the way this system operates; i.e. an explanation of the system structure.

One can also claim that the type of analyses mentioned above can also be conducted without using explanatory models. The conclusions drawn in the cases of NavalTrans and ElectTrans can also be drawn in other ways, or possibly by just intuition of an expert in these systems. The added value is not that the drawn conclusions are all unthinkable and surprising: it is the fact that an explanatory model makes the task easier and less prone to reasoning errors. Being in a formalized and quantified form, these models are internally consistent and integrated depictions of the key processes within a system. Considering the difficulty of reasoning about a set of non-linear feedback processes, or about the interaction of a large number of actors, the models are very useful. However, even without conducting any simulations, this structure alone helps to develop a better understanding of the system and the ways it may possibly behave. In most cases, we used the model structure for understanding the observed phenomenon. The cases of stagnating renewable generation growth and the system's insensitivity to increasing carbon penalties are such examples from the analysis we have conducted with the ElectTrans model. Similarly, when we aimed to understand how a potentially superior novelty (i.e. steamships) could not dominate the system, and just experience a limited penetration level, the structure of the NavalTrans proved to be helpful.

The added value of a general framework for developing explanatory models is twofold. Once there is a general framework that provides guidance in developing models for studying a certain type of problem, the modelling process is much easier and less prone to key omissions in the system boundaries. In Chapter 7, we discuss how the actor-option framework can guide the development of a transition model. Later, in Chapters 8 through 10, we demonstrate how we benefit from these guidelines in developing the discussed models. It is clear that the framework provides a structure for the task at hand. This can be considered as an added value of having a framework in a single modelling study.

A more important benefit of having such a framework is that it provides a common conceptual language that can be used to cross boundaries of particular cases. Using such a language, it is possible to transfer insights among cases, or carry the case specific insight to the higher level about the transitions, in general. Briefly going over the modelling studies, it is possible to recognize the indications of such added value.

In the waste management case, we discussed the importance of a ‘social control loop’ that puts pressure on the incineration options, and constrains the option’s role in the system; the system actors react to the emission levels caused by incineration, the air quality becomes a high priority issue, and this, in a nutshell, causes the decrease in the intensity of the incineration activity of the actors. An immediate consequence of utilizing an option (e.g. pollutant emissions) is linked to an important issue for the actors (e.g. air quality). Once the actors observe that the system develops in an undesirable direction with respect to the issue, this triggers a reduction in the utilization of the option. This chain constitutes the control loop that suppresses the
intensity of incineration in the waste case. Considering the control loop in general terms, one can consider why such a loop is not operational in the electricity supply case, or if it is possible to engineer/introduce one in that context. There is certainly some link between what the end-users find important (i.e. global climate change) that are related to the consequences of using the fossil fuels (i.e. carbon emissions). At least, we observe efforts towards establishing such links through informing the public about the impact of carbon emissions on global climate change, for example. However, it does not seem to work. Comparing the two cases, we can explain the reason why it does not, and probably why it will not. First, the aforementioned link is not established very strongly; there is no unquestionable consensus about the impact of emissions on the climate change. Secondly, and more importantly, the consequences of using the fossil fuels are not immediate (i.e. cause and effect decoupled in time). Therefore, the social control loop is not operational in a practical timeframe. If this (operationally) missing link can be established, it may be possible to suppress the share of fossil fuels endogenously in the system. The correspondence with the general form of the control loop, as well as the differences among the cases can be seen in Figure 11.1.

![General form of the control loop](image)

**Figure 11.1. Different manifestations of the control loop in different cases**

In *NavalTrans*, we show that in the presence of capacity-sensitive passengers/merchants who do not immediately forget about their negative assessments about the steam-ships, this type of ships may fail to realize its potential if the capacity build-up is slow. In *ElectTrans*, we argue that the stagnation of the growth in the renewable generation can be due to the diminishing green certificate prices. These two observations look case-specific, but when considered
at a general level they are about the same kind of phenomena, and the observations from the *NavalTrans* case may be considered as a serious warning for the renewable generation technologies’ future. In the steam-ship case, once the actor makes a poor assessment, there is a time delay until the next time the actor considers the option seriously (i.e. forgetting time). The same holds for the electricity case; once an end-user makes a poor assessment about the renewable options, the actor goes for an alternative supply option. Until this option is written off, the actor will not consider a capacity investment (hence, the investment in the renewable options) seriously. Moreover, in both cases the poor assessment is related to the balance between the demand and the provision/supply capacity: long waiting times due to vessel insufficiency, and low green certificate payments due to demand insufficiency. As a result, there is a strong correspondence (i.e. a strong structural analogy) between these two cases in terms of the general concepts of the framework. If this is the case, the failure of the steam-ship despite having a great development potential can be considered as a caveat for the case of renewable generation options. Failing to keep the balance between the growth of the demand and the supply may yield a similar problem also in the latter case.

One of the major issues investigated in the electricity supply case was the empowerment of the coal-based central generation option, and the strong comeback it demonstrated in some scenario experiments. The comeback is mainly driven by the rapid change in the economical profitability of the coal-based generation facilities. This explanation does not say much about general transition dynamics. However, the explanation can be generalized by translating it into the concepts of the framework. The economical profitability is a disembodied property of the coal-based options, and it is reversible. Additionally, the preference structures of the actors are dominated by a single issue (i.e. profit maximization), which is related to this reversible property. As a result, the conclusion from this specific case translates into the following; a comeback of an unwanted option, or a backlash of a promising option can happen quite rapidly in the socio-technical settings where the decisions of the actors are dominated by a single reversible option property. This way the conclusion from the specific case can be generalized and considered as a conclusion/observation on transition dynamics.

The observation on the impact of user preferences on the development and diffusion of a novelty from the *NavalTrans* experiments is also generalizable in the same manner. Those experiments show that in cases where the actor groups are clustered far away in terms of their preferences with respect to a certain issue, the novel option may not penetrate the whole system, and get stuck in a small actor niche. In the case of having a development mechanism that does not depend on the scale of utilization, the penetration of the novelty may still take place, but in a terraced manner.

To sum up, a set of examples from the modelling studies, which are briefly discussed above, demonstrates the added value of using explanatory simulation models, and also of having a general framework that can be used to develop such models for transition processes in socio-technical systems.
Conclusions and Reflections

12.1. Overview of the overall objectives of the study

This study is focused on dynamics of transitional change in socio-technical systems in general, and on analytical approaches for understanding these dynamics in particular. The research was motivated by the limited progress achieved so far towards understanding such dynamics of change (e.g. how can very different manifestations of transitions in similar systems be explained?). In that respect, we developed an analytical perspective that can be used to study transitional change processes, and can enhance the state of our understanding about the nature of such processes.

In our preliminary review of the state-of-the-art in transition studies, we identified both methodological and conceptual issues that may be hampering the progress in understanding dynamics of transitional change. So far, analyses relied heavily on qualitative approaches, which are mainly descriptive in nature. Despite their merits, such approaches do not offer much to explain how and why transitions unfold the way they do. While computational approaches stand as promising options for studying such dynamic complexity, the possible extent of their use in analyzing transition dynamics was not investigated thoroughly. Furthermore, existing concepts and theories on transitional change are either unexploitable (incompatible) with computational approaches, or are too abstract to translate insights to practical forms for an actual policy context.

Motivated by these issues, this study focused on both methodological and conceptual issues, while aiming to contribute to the set of analytical perspectives used in the transition dynamics field. The objectives of the study along these two frontiers, i.e. methodological and conceptual, can be summarized as follows:

- **Methodological**: Investigation of how and to what extent simulation-supported analysis, as a particular computational approach, can be utilized in studying complex dynamics of transitional change.
- **Conceptual**: Development of a general conceptual framework for modelling socio-technical systems in order to study their transitional dynamics.
The main conclusions and outcomes of the study are discussed according to these two frontiers. In Section 12.2, the major results of the methodological investigation are presented. This is followed by the discussion on the outcome of the conceptual framework development process, i.e. the actor-option framework, which is given in Section 12.3. Section 12.4 is devoted to the conclusions from our investigation of the proposed framework based on its application to three different transition cases. Finally, the chapter concludes with reflections on the study, addressing some shortcomings and future directions of research (Section 12.5).

12.2. Simulation-supported analysis of transition dynamics

In this section, we summarize our findings based on a detailed methodological investigation. These conclusions are mainly related to the degree of fit of the simulation-supported analysis approach to the transition dynamics problem, different purposes that can be served by the approach, appropriateness of the existing modelling paradigms, and major limitations of the approach.

a. Problem-approach fit

We investigated the suitability of simulation-supported analysis to the nature of transition dynamics problem. Two different sets of aspects are highlighted as a result of this investigation. The first set is related to general characteristics of transition studies. The second set is more related to the nature of the systems being studied in the context of transitions.

Transition studies are all about a system's shift from one state into another. In that respect, the emphases in research questions in the transition studies field are on this shifting process, rather than on end states. Basic premises that are observed to be common in the field are related to the path-dependent nature of the transition processes, and unpredictability and impossibility of predetermination of these end-states. Approaches that are predictive (e.g. forecasting) or prescriptive (e.g. optimization) in nature, or approaches that focus on state of a system at a particular point in time (e.g. equilibrium analysis) are evaluated to be in conflict with the basic premises of the field. As a result we conclude that in order for an analytical approach to be in coherence with the basic foundations of the transition field, it has to carry two basic characteristics; it has to be descriptive/explanatory in nature, and it has to focus on the time-trajectory of the change process.

By definition, an analysis of transitional change relies on a wide system boundary that covers various aspects of a societal function (e.g. institutions, practices, technology, infrastructure, regulations). Societal (or more specifically socio-technical) systems within such broad boundaries incorporate features that constrain the set of approaches that can be used to analyze these systems' behaviour over time. We find especially two of these features very troublesome for analyzing transition dynamics. Firstly, these systems incorporate (non-linear) feedback processes, which operate at different spatial and temporal scales. Secondly, the social aspect of these systems comprises interacting actors, which are heterogeneous and dynamic in their objectives, norms, and preferences, for example. Although it is possible to study these features to get a snapshot of the system (e.g. how things are connected/interrelated in the system, what kind of objectives an actor has), overall system behaviour is beyond the limits of qualitative reasoning when these features are considered simultaneously. In that respect, we claim that it is not likely to achieve significant progress in understanding dynamic complexity of transitional change by just relying on qualitative approaches. As a result, we recognize an
imminent need for computational approaches to progress our understanding on transition dynamics.

Considering mainly the two sets of issues discussed above (i.e. about the general characteristics of transition studies, and about the nature of societal systems), simulation-supported analysis of transitional change with quantitative models of societal systems is evaluated to fit the challenge at hand. In addition, the wide utilization of the approach that we observed in the progenitor fields of transition dynamics (i.e. diffusion studies, integrated assessment, evolutionary economics, complexity) provides supporting evidence for such an assessment. Although we do not propose the simulation-supported analysis as the methodological ‘magic bullet’ of the transition dynamics field, we see it as a key component in the methodological toolbox, despite its limited utilization so far.

b. Potential uses of simulation-supported analyses

The previously discussed assessment of the problem-approach fit is based on general characteristics. However, both the research domain of transition dynamics, and the application of the method encompass some variety. We investigated different potential uses of simulation models considering different challenges within the transition dynamics field. Based on this investigation, we identify three expedient uses of simulation models that can contribute to studies on transition dynamics. These three uses, which constitute a preliminary typology of model-use in transition studies, are summarized as follows:

- **Case-specific insight development**: Exploration of plausible transition trajectories for a particular socio-technical system using models that have strong links with the actual system (e.g. rich in detail, and empirically grounded)
- **General insight development**: Studying behavioural consequences of a process, or of interactions between a set of processes under different circumstances using simple and generic models (i.e. no correspondence with a particular actual system)
- **Theory development and refinement**: Evaluation and refinement of a proposed theory that claims to explain transition dynamics using models that are developed based on the premises of the theory (e.g. do the explanantia of the theory actually explain transition dynamics, as is claimed?)

Two aspects of this preliminary typology need to be explicitly highlighted. First, simulation-supported analysis is traditionally associated only with the first type of model-use. Such an association undermines the potential of the approach by overlooking the other two uses. Secondly, these three uses are very different in nature: the level of reliance on empirical data, detail level of the models, testing/validation requirements, and experimentation schemes are all different for different uses. Therefore, general methodological discussions on merits, requirements, or shortcomings without explicitly referring to one of these uses are likely to be flawed. By explicitly distinguishing these different uses of simulation models, we provide a structure that can guide future methodological discussions in the field, and this is expected to increase the clarity and effectiveness of such discussions.

c. A critical review of modelling paradigms

The previous step was on how models can be used. In the second part of our inquiry, we focused on how such models can be developed. Developing quantitative models of a target system, and analyzing these models’ behaviour through simulation experiments is a defining characteristic of several research communities. Despite having commonalities, modelling
perspectives dominant in these communities show some fundamental differences. We reviewed four different modelling paradigms, and focused on the extent to which these can be used to explore transition dynamics, and contribute to general understanding about underlying processes. These modelling paradigms are agent-based modelling, econometrics, micro-simulation, and system dynamics.

Among these four, econometrics and micro-simulation are evaluated not to be appropriate in the problem domain of transition dynamics. First of all, the overall objective in both approaches can be summarized as ‘forecasting policy implications in the prevailing system structure’. Models to be used for this objective are specified based on extensive historical data based on the assumption that the structure of the system will stay intact within the time horizon of the analysis: an implicit assumption that is totally incoherent with the basic foundations of the transition problem. Secondly, numeric precision of the model at a certain point is generally more important than the dynamic behaviour of the system. Related to that, the models that characterize these two approaches are predominantly black-box models: they generate point predictions without referring to actual processes that drive system behaviour. Therefore, they are not appropriate for studying the underlying processes of transition dynamics. Considering these issues, we conclude that the prospects of these two approaches obtaining a place in the toolbox of transition dynamics scholars is quite unlikely.

Both agent-based modelling (ABM) and system dynamics (SD) are subject-field independent approaches that aim to analyze dynamic phenomena especially in socio-economic systems. They avoid a predictive or prescriptive mode, and adopt a more descriptive stance. They aim to understand dynamic phenomena via describing the way components of the related system interact and change over time in the form of a model, and analyze this model’s behaviour via simulation experiments. Based on these similar characteristics we evaluate both paradigms as appropriate candidates for transition dynamics studies. When it comes to differences, major issues seem to be related to the dominant conceptual perspectives. We especially focus on how these differences relate to perspectives within the transition studies domain, and aim to highlight issues that are relevant for methodological choices in a simulation-supported analysis on transition dynamics.

Both paradigms impose, implicitly or explicitly, a conceptual frame that conditions the way we look at the target system, and what we focus on as sources of complex dynamics. The level of congruence of these frames with the dominant conceptualizations of transitional change in the field is of primary importance for assessing whether one of these paradigms naturally fit the transition dynamics problem better. Therefore, we analyzed the common conceptual frames imposed by these approaches, and discussed these in relation to the concepts used to explain transition dynamics, and related processes.

1 Looking at the issue from another angle, it can also be said that the transition dynamics topic is unlikely to be popular among scholars in micro-simulation or econometrics fields.
in socio-technical systems. In order to structure such an analysis, we categorized the used conceptual frames with respect to two properties, and came up with a four-type categorization of conceptual frames used in simulation modelling, in general (Figure 12.1).

Briefly, a macro-level conceptualization focuses on the level of the phenomena under scrutiny, whereas a micro-level one is based on individual elements of the system. Additionally, a system’s behaviour can be seen as a consequence of continuous processes, or relations between system elements (i.e. relation-driven), or as a consequence of actions and/or events that alter the states of these elements (i.e. action-driven).

According to this classification, SD imposes a relation-driven conceptualization, and SD models predominantly have a macro-level focus. Although, the approach does not rule out micro-level conceptualizations, and despite some examples that can be characterized as type-III, the natural tendency of the paradigm is towards residing in the upper-left quadrant (type-I). ABM relies on actions of agents as the driver of system behaviour. Depending on what is seen as an agent, ABM studies may fall into type-II or type-IV category. However, we observe that a micro-level conceptualization is the dominant one.

When we studied the different ways systems in transition are conceptualized in the transition dynamics field, we concluded that it is not possible to identify a single quadrant from Figure 12.1 as the dominant one. Some conceptualizations rely on regime and niches as emergent entities in explaining transitional change, and this corresponds to a macro-level focus. On the other hand, some other perspectives treat regime and niches as social boundaries, and rely on social groups, firms or individuals that reside within these boundaries in explaining transitions (micro-level conceptualization). Additionally, in some cases both macro and micro level elements are used in conceptual models; e.g. emergent niches coupled with individual actors. Such a variety also exists for ‘drivers of system behaviour’. Actions of heterogeneous actors are discussed as one of the primary sources of dynamic complexity. This apparently suggests an action-driven conceptualization. Moreover, transitional change is also frequently depicted as a long-term continuous change process. Additionally, it is argued that slow and continuous change processes (e.g. resource depletion, pollutant accumulation, norm formation) accompany faster actor actions in shaping the transition dynamics, and play a significant role in that. As a result, transitional changes are conceptualized to be driven by a combination of discrete actions and continuous processes.

In conclusion, the transition field relies on rich conceptualizations that span almost all quadrants of our classification, and none of the aforementioned modelling paradigms is able to embrace such richness in their traditional forms. In that respect, sticking solely to one of these paradigms may be constraining in studying transition dynamics, and that way it may not be possible to get the most out of simulation-supported analysis. Therefore, we claim that models that would be developed based on such rich accounts of transition processes demand a synthesis of aspects from different modelling paradigms (i.e. hybrid models). For this purpose, investigating different modelling approaches in an unbiased manner is important in order to reveal the aspects that can be synthesized for studying transitions. The model developed for analyzing the Dutch energy transition, which is discussed in Chapter 10, is an example of such an inter-paradigm model, which combines concepts from both SD and ABM.
However, we do not want to rule out the potential contribution of single-paradigm models in transition studies. The transitions field has a broad coverage of different perspectives and research objectives. Not all studies focus on a comprehensive analysis of transitional change; in some cases it is a smaller sub-problem that needs to be addressed within the big picture. Moreover, not all transition processes incorporate all the aforementioned conceptual richness. In these cases, the problem at hand may scale down to a form that properly fits one of these modelling paradigms; i.e. ABM and SD.

In summary, we conclude that modelling and analyzing transitional change requires combining merits of both ABM and SD, and there is no clear-cut choice of modelling paradigm for transition studies. Therefore, a methodological orthodoxy that would impose a certain modelling paradigm for studying transitional change is limiting. Instead of looking at the transition phenomena from a frame imposed by a precariously chosen modelling paradigm, we should be looking at the available modelling paradigms in order to identify the aspects to combine for addressing the conceptual models we develop for transitional change.

d. Limitations and shortcomings of simulation-supported analyses

As a result of our assessment of using simulation models for studying transition dynamics, we identified a set of issues that limit the extent of use, and pose some difficulties in simulation-supported analyses.

A major issue is quantitative representation of social aspects; i.e. modelling the social. It is possible to identify some regularities in social behaviour. However, we came to the conclusion that the reflective and adaptive nature of social elements (e.g. individuals, groups, organizations) makes it impossible to formalize how they will behave exactly. Unlike purely techno-physical systems, the structure of social systems may change, or there may be ‘sleeping structures’ within the system that get active under unusual circumstances, such as a transition. This issue rules out predictive use of simulation models in transition studies. Hence, such a use is excluded from our typology of model-uses.

Emergence of novelty (e.g. new social practices, new artefacts) is a path dependent process that is influenced by many contingencies. Such processes can be endogenously represented in simulation models. However, we claim that outcomes of such models are meaningful only if they are used to analyze novelty emergence patterns (e.g. which innovation policy leads to more technological variety?), and not for telling anything about particular novelties that will/may emerge (e.g. what kind of new fuel technology will emerge?). This may constitute a limitation for the extent of utilization of simulation-supported approaches.

When models are to be used for general insight development, or for theory development, we claim that the aforementioned two issues (modelling the social, and modelling the novelty creation) do not damage the potential merits, considering the very nature of these different model-uses. As we discuss in further detail in Section 2.4, this is mainly due to the loose, or non-existent correspondence of such models with a particular real-world system. However, it is not the same with models that correspond directly to a particular real-world socio-technical system (models for scenario/policy experimentation). Extra attention and effort are needed in developing this type of models in order to embed some room for change into the model, ex ante. This includes explicit inclusion of social adaptation and reflexivity as much as possible.
Conclusions and Reflections

(e.g. coverage of plausible alternative social reactions, and behavioural routines), and of technological novelties that are plausible to appear in the future. Besides these implications on the model development process, these issues also influence the way simulation experiments should be conducted, and model output should be interpreted. Considering uncertainties and the role of contingencies on emergence of novelties or social adaptation, conventional ways of experimentation based on a limited number of experiments is not satisfactory. Additionally, these models can only be utilized as platforms for developing insights on dynamic behaviour, rather than as forecasting machines.

12.3. The actor-option framework

The second part of the research is on developing a general conceptual framework for modelling socio-technical systems to study their transitional change dynamics. The development process was guided by two important requirements: first of all, the conceptual framework should be suitable for simulation-supported analysis as advocated in the first part of the study. The typology of model-uses introduced in Section 2.3 is taken into account in shaping the nature of this conceptual representation, since the typology specifies different types of models that may be of interest in the transition dynamics field. Secondly, the potentially problematic issues raised in Section 1.4 of this dissertation regarding the current state-of-the-art in transition conceptualizations should be addressed as much as possible. Briefly, these issues can be summarized as follows:

- **Structuralist stance:** Ignorance of the social actors in their descriptive and/or explanatory accounts. Either the concepts used are explicitly isolated from the behaviour of social actors, or these actors are not included in the analyses in a structured manner, despite acknowledging their potential importance.

- **Aggregates of non-equivalents:** Reliance on aggregate concepts with mixed nature (e.g. social and techno-physical) such as niches and regimes. The behaviours of these concepts are hard to analyze, and it is difficult to empirically support such analyses in a more or less objective manner. This leaves too much room for subjective interpretation in discussing the developments in the system in terms of these aggregate concepts.

- **Policy relevance:** Adoption of a high abstraction level in conceptualizations. This makes it difficult, or almost impossible to transfer insights developed at that high abstraction level to an operational level in a particular real-world policy context.

We developed the actor-option framework considering the need to address these shortcomings. The development process is presented in detail in Section 3.1. In the following sub-sections we briefly introduce the actor-option framework as the main outcome of the process. In doing so, we first introduce the basic building blocks used to develop conceptual models of socio-technical systems according to the actor-option framework. After discussing the general structure according to which these building blocks interact, a set of mechanisms that are responsible for the changes of these blocks within this general structure are given.

**a. Basic building blocks of the actor-option framework**

Transitional change dynamics in socio-technical systems are a result of conjoint changes in social and techno-physical aspects of these systems. These aspects rarely change along coherent trajectories as a whole; rather they both have their own internal dynamics, which are influenced by the dynamics of the other. Additionally, the nature of these aspects, as well as
how they change over time, is significantly different. As a result, we concluded that in order to explain transition dynamics properly, dynamics on social and techno-physical aspects should be considered simultaneously, but separately.

On the social side, social actors (e.g. individuals, groups, organizations, firms) are the main motor of change in the socio-technical systems. In that respect, explicit recognition of these actors, and of variety among them with respect to transition-related behaviours are important. Therefore, one of the building blocks of the framework (i.e. *actor*) is considered for representing these social elements. The state of the techno-physical world is very important in shaping the behaviour of the *actors* in the context of a societal function. Especially, the techno-physical elements that constitute alternatives for the *actors* regarding the fulfilment of the societal function are of primary importance in this sense. The second building block of the framework, i.e. *option*, corresponds to such alternatives. Such an explicit separation of the social and techno-physical aspects in our representation also addresses the problem of very aggregate concepts with mixed nature in the existing conceptualizations. *Actors* and *options* are still aggregate concepts, but they represent relatively homogenous entities in nature, whose behaviours are easier to analyze empirically.

The importance of actor heterogeneity in shaping transition dynamics is a frequently mentioned, but poorly analyzed issue in the field. The type of heterogeneity that matters for transition dynamics is a key issue in deciding on the way actors should be characterized in a conceptual representation. We suggest, firstly, explicit representation of some key aspects that may differentiate actors in terms of their behaviour, and especially choices, within a transition context; *preferences*, *references*, *commitments*. Secondly, we propose categorizing actors into four different role types, which differ in the impact on the system of the choices made by an actor. These four actor roles that we identified in our investigation of case studies are given in Table 12.1.

<table>
<thead>
<tr>
<th>Actor role</th>
<th>Description</th>
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<tbody>
<tr>
<td>Regulators</td>
<td>Intervene the system via setting new regulations, and (indirectly) supporting/opposing certain artefacts or practices.</td>
</tr>
<tr>
<td>Opinion groups</td>
<td>Influence the system via their opinions (e.g. being against, favouring), and may change the way an alternative is assessed by other actors in the system.</td>
</tr>
<tr>
<td>Providers</td>
<td>Provide and maintain necessary and supplementary means of fulfilling a societal function (e.g. infrastructure, service network)</td>
</tr>
<tr>
<td>Practitioners/ Users</td>
<td>Choose and utilize available options for fulfilling a societal function.</td>
</tr>
</tbody>
</table>

As a result of our investigation, we observed that narrowing the techno-physical part of a socio-technical system down to a set of technological artefacts misses an important part of the picture in explaining transitional changes. In a transition context, actors do not consider artefacts in an isolated manner, but these artefacts constitute viable options only with their social, economical and infrastructural embedding in the system. Therefore, an option should be represented in a way that incorporates properties directly related to the artefact, as well as properties related to the embedding of it in the system. Based on this conclusion, an option in the actor-option framework is a broader concept than a stand-alone technology, and it
is characterized by, so called, embodied and disembodied properties. Embodied properties are related to the techno-physical nature of an option, and they can be observed even when the option is isolated from its socio-economical context. Disembodied properties are related to the context in which the option functions. Disembodied ones can be further categorized as provisional (about the way an option is made available), or as practical (about the way/intensity an option is being used).

b. Actor choice as the keystone of system change
Actors’ choices in relation to the alternative means of fulfilling a societal need are the main motor of change in a transition context; e.g. actors choose which option to support, use, and/or invest in. Based on this perspective, the main frame of the conceptual representation, which interlinks actors and options, is built around actors’ option-related choices (Figure 12.2). According to this frame, actors’ choices determine the overall functioning of the system, and influence options’ development. Both of these changes feed back to the actors via information flows, and may alter the course of their choices. The actor choices are based on this information, as well as other aspects that characterize an actor’s behavioural identity in the transition context, such as actor’s preferences, references and commitments. In other words, actors are not conceptualized as economically rational (i.e. homo economicus); instead, actors’ choices are conceptualized to be conditioned by their social surrounding and choice history besides purely economical criteria.

c. Mechanisms of change
As mentioned earlier, the general conceptual representation aimed with the actor-option framework is primarily to explain transitional change in terms of endogenous processes of socio-technical systems. Therefore, the question of whether there is some similarity among socio-technical systems with regard to transition-relevant internal processes, or not, was a very important one along the development process. The investigation on case studies, as well as theoretical literature revealed a set of processes (i.e. mechanisms) that can be recognized in a variety of socio-technical systems in their generalized forms. We observed that case-specific instances of these mechanisms are strongly influential in the way transitional changes unfold in most of the cases studied.
Following the main frame of the proposed conceptual representation, these mechanisms are primarily related to changes of options in relation to actors’ choices, changes of actors’ information about their environment and available options, and changes in the identity of the actors that condition their choices. The set of identified general mechanisms that constitute the drivers of change in the actor-option framework are given in Table 12.2.

<table>
<thead>
<tr>
<th>Mechanisms on option change</th>
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<tbody>
<tr>
<td>Experience-driven change</td>
</tr>
<tr>
<td>(Irreversible) Development in option properties as a consequence of accumulating provider and/or practitioner experience with the option.</td>
</tr>
<tr>
<td>Scale-driven change</td>
</tr>
<tr>
<td>(Reversible) Changes in option properties dependent on the scale of actors’ involvement with the option.</td>
</tr>
<tr>
<td>Resource-driven change</td>
</tr>
<tr>
<td>Development in option properties as a consequence of actor resource (e.g. economical, intellectual) allocated to an option.</td>
</tr>
<tr>
<td>Exogenous change</td>
</tr>
<tr>
<td>Option property change due to developments beyond the boundaries of the socio-technical system (e.g. inventions in another system)</td>
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</tbody>
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<table>
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<tr>
<th>Mechanisms on actors’ knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual learning</td>
</tr>
<tr>
<td>Information update via direct experience and/or observation</td>
</tr>
<tr>
<td>Social learning</td>
</tr>
<tr>
<td>Indirect information update based on information known by other actors in the system</td>
</tr>
<tr>
<td>Learning from external sources</td>
</tr>
<tr>
<td>Indirect information update based on exogenous sources such as scientific reports, marketing campaigns, etc.</td>
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<table>
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<tr>
<th>Mechanisms on actor’s identity</th>
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<tbody>
<tr>
<td>Reference formation</td>
</tr>
<tr>
<td>Change in actors’ requirements/expectations based on interactions with an option and/or with other actors</td>
</tr>
<tr>
<td>Commitment formation</td>
</tr>
<tr>
<td>Change in the level of commitment as a result of accumulating tangible/intangible assets related to a certain choice.</td>
</tr>
<tr>
<td>Preference structure change</td>
</tr>
<tr>
<td>Change in actor preferences due to observed problems, or landscape developments such as cultural change.</td>
</tr>
</tbody>
</table>

In summary, our inductive analysis of case studies from the literature resulted in a conceptual framework, which identifies building blocks, and a set of mechanisms. These mechanisms explain how these blocks interact and change, and consequently shape the system’s transition dynamics. Both building blocks and mechanisms are claimed to be key, and to a great extent sufficient for explaining and analyzing transition dynamics in socio-technical systems. Considering the variety of system configurations encountered during our reviews, we conclude that it is not possible to develop a single universal model that explains how a system’s transition unfolds (i.e. a dynamic hypothesis), at least, at a policy-relevant abstractions level. However, the impossibility does not arise due to variety of elements/processes in these systems, but mainly due to the variety in the ways these elements/processes are interlinked. In that respect, the actor-option framework is not a general transition model, but it is a compilation of modular concepts (i.e. actors, options, and mechanisms) for developing models that are case-specific, or generic at some level.
12.4. Investigating the actor-option framework through application

In the third part of the study, we apply the actor-option framework in three modelling studies. Through these modelling studies, we aim to present demonstrative applications of the framework in developing simulation models for analyzing transitional changes. Additionally, we also use the studies to investigate the extent to which the framework can serve as a general conceptual grounding, which involves identification of conceptual and practical limitations. Finally, the analyses conducted the models developed provide evidence regarding the basic premises of the framework.

Two of the studied cases are historical transitions; transition in the Dutch waste management system, and a transition in the British naval transportation system. The third case focuses on current state of the Dutch electricity system, and its plausible change dynamics. Primary reason for choosing diverse socio-technical contexts is related to exploring the extent to which the framework is a (contextually) general one. As we discuss in Section 11.2, we conclude that the basic concepts of the framework (i.e. actors and options) can successfully be applied to these different contexts without difficulty. The option concept, in the way it is characterized in the framework, is used to represent a diverse set of things such as artefacts, processes, and services in these three different cases.

Additionally, we see that the mechanisms introduced in the framework are applicable in these different contexts: the key processes taking place in the studied socio-technical systems can all be classified as specific instances of these general mechanisms, and they are represented using these general mechanisms in the developed models. An advantage of using historical transition cases is the presence of detailed ex-post analyses about important developments during the transition. This allowed us to evaluate the sufficiency of the actor-option framework in covering social and techno-physical developments that played an important role in those transitions. In this evaluation, we observed that all those key developments could be formalized as instances of the mechanisms of the framework. In other words, the ex-post analysis of processes that drove these historical transitions can be re-constructed using the actor-option framework in a formalized manner, without leaving out major processes or developments.

For the third case, we lack such a detailed ex-post analysis since it is an ongoing transition case. While investigating if the ElectTrans model cover the key processes, we relied on other models developed for the Dutch electricity supply system as the benchmarks. Based on these observations and comparisons, we conclude that the models developed in these three studies are comprehensive in their scope and successful in representation. These provide us important evidence about the generality of the framework in terms of its application context.

Besides, we also show that the framework can be used to support analyses at differing aggregation levels by developing models that differ in aggregation. Among these the WasteTrans model is the most aggregate example, whereas the ElectTrans model has the least aggregation in terms of both the options and the actors. The variety in the character of the main developments (e.g. social, regulatory, or technological) that drive the transitional change in these three transition cases is also an opportunity. This way, we investigated the extent to which the framework can be used for analyzing different aspects of transitional changes. As we discuss and show in the modelling studies, the models developed using the framework can be used to explore social, regulatory, and techno-physical aspects. Among these, the framework is observed to be strongest on the techno-physical aspects.
In Section 2.3 of the dissertation, we discuss three different purposes for which simulation models can be utilized in transition studies. During the modelling studies, we also link to that discussion by using the developed models in different ways. As we discuss in Section 11.4, both NavalTrans and WasteTrans primarily serve testing and development purposes. Furthermore, the NavalTrans model is used for developing general insights about the impact of actor heterogeneity on transition dynamics during the experimental analyses. Finally, the ElectTrans is used specifically for developing case-specific insights about the plausible dynamics of the Dutch electricity system. As a result, the models presented in Chapters 8 through 10 constitute examples for the different model-uses discussed in the dissertation. This way we further clarify the differences between these three uses and their potential contributions by examples.

The actor-option framework builds on three fundamental premises briefly about the importance of explicitly addressing the social actors, avoiding the aggregation of system elements of different natures, and staying at a policy-relevant abstraction level. During the analyses with the three models, we identify a set of circumstances that support the importance of these premises in explaining the observed transition dynamics. In both NavalTrans and WasteTrans cases, it is observed that the separate representation of differing types of system actors is vital in capturing and also explaining the developments underlying the transition processes. Furthermore, a set of experiments with NavalTrans shows that the heterogeneity among a particular type of system actor can be the principle factor shaping the overall transition pattern. The importance of the policy-relevant abstraction level is verified in the electricity supply case with a set of examples. Mainly due to the complicated physical and institutional structure of the system, it is not straightforward to foresee the system level implications of even the simplest policy changes. Therefore, experimentation with such policy changes is easy to implement and validate when the model resides at the abstraction level of such policy measures, which is a very important added value for the analyses.

The three modelling applications of the framework, and the simulation-supported analyses conducted with these models provided us the opportunity to investigate the limitations of the framework. We focused on two categories of limitations; the conceptual limitations are briefly related to the difficulties encountered in representing particular issues using the elements of the framework. The most important limitation is related to the endogenous representation of the institutional change processes. Although it is possible to include institutional changes into the analyses in the form of scenarios as in the case of ElectTrans, or very abstract endogenous indicators as in the case of WasteTrans, the framework is evaluated to be limited in terms of institutional change mechanisms. A similar limitation is also observed regarding the endogenous representation of the sudden changes within the system, such as crises, internal shocks, or accidents.

The practical limitations are related to the difficulties in representing the conceptual models developed using the framework in quantitative simulation models. This includes quantification of the concepts, and formalization of the mechanisms. The quantification of the mechanisms related to the behavioural identities of the actors is observed to be one of the most challenging processes, in this respect. The difficulty mainly arises due to the possibility of using a vast range of quantities to initialize such mechanisms. As it is demonstrated in the WasteTrans case, such a limitation can be overcome to an extent by supporting the conclusions with
extensive sensitivity analyses in order to demonstrate the robustness of the results under different possible quantifications.

A second practical problem is encountered in the case of electricity supply system, where the developed model, i.e. ElectTrans, is rich in detail and low in the aggregation. A proper analysis of the transitional dynamics using the model requires considering a vast number of contextual scenarios, as well as social and technological uncertainties embedded in the model structure. Therefore, simulation-supported analysis should not be conducted in a traditional manner, i.e. a limited number of simulation experiments based on a single quantification/initialization of the model. Instead, an extensive exploration, which demands simulating the model with numerous settings and analyzing the resultant dynamics, is required. We observe that this can hamper the extent of utilization of the framework and the simulation-supported analysis approach. Therefore, novel experimental analysis approaches that rely on more extensive sets of simulations are needed to supplement the use of the framework in detailed modelling cases. Exploratory modelling and analysis (EMA) is a good example for such novel approaches with successful applications in various domains (e.g. Agusdinata 2008; Lempert, Popper et al. 2003; Pruyt and Hamarat 2010).

12.5. General reflections and prospective directions of research

In this section, we take a step back, and reflect on this research as a whole. The overall contribution of the study can be labelled as an analytical perspective, which is proposed for analyzing transitional change processes in socio-technical systems. The perspective consists of developing quantitative models of socio-technical systems based on the actor-option framework, and exploring the behaviour space of these models through simulation experiments. The following sub-sections focus on a set of issues related to basic assumptions and limitations of this analytical perspective. Doing so, we aim to highlight proper ways of utilizing the approach, as well as pointing out potential directions for future research.

a. Influence of systems thinking

The intellectual backbone of this study, which shapes the way it approaches the transition issue and the methodological search, is significantly shaped by the founding ideas of systems thinking. Certainly, changing contextual conditions, surprise events, and crises play very important role in influencing transition dynamics. However, it is also clear that the way related elements (e.g. actors, technologies, resources) interact in the context of a societal function, and the way they respond to such crises and/or surprises triggers and shapes transitional changes. Therefore, transition dynamics can be understood to some extent by understanding the interaction of those related elements, and the structure of the whole they constitute; i.e. a socio-technical system. At this point, the systems perspective provides an appropriate intellectual and methodological guidance towards developing such an understanding.

It is claimed that the proposed approach, which is a particular manifestation of the systems thinking perspective in the transition field, is an important and potentially effective one. However, it is not claimed to be the ‘magic bullet’ for the transition problematique; it will not be able to provide answers to all questions regarding the transition puzzle. The approach is promising in progressing towards linking the system structure to the dynamic complexity observed, but there is more in it; such as understanding the isolated behaviour of important
social actors, or processes related to establishment of informal institutions. In that respect it is clear that other qualitative and quantitative approaches are also needed to supplement the contribution of the proposed approach in order to enhance insight and understanding on transition dynamics.

b. Focus on system’s behaviour in general
As a natural consequence of adopting a systems perspective, the focus of this study is on the system (i.e. socio-technical system) of interest rather than a special dynamic phenomenon (i.e. transition). It is aimed at understanding how a particular system structure leads to certain behaviours, transitions being a special subset of such behaviours. In that respect, what makes a socio-technical system resistant to change (or what is the source of system inertia?) is a question of interest for this approach, as much as what drives a transition. Simply put, the analytical perspective is not proposed just for investigating successful transitions; it is a perspective proposed to analyze why socio-technical systems behave the way they do. This extension of scope, which comes as a natural consequence of taking system structure as the unit of analysis, is important especially for transition-related policy studies. Focusing only on transition cases help to understand success stories better, and to identify some conditions of success. However, designing policy intervention schemes to steer socio-technical systems along a course of change can only be achieved if the plausible responses of the socio-technical system are properly comprehended.

c. Deterministic stance
The models developed according to the proposed analytical framework are deterministic depictions of the systems in focus. Although both the conceptual representation, and implementation of simulation models do allow non-deterministic applications, we deliberately take a deterministic stance. At a first glance, this may look inconsistent with ‘agency’ of social actors, and improper in transition analysis where surprise events are important. Both points would be right, if the proposed perspective was based on a one-to-one correspondence with particular individuals and/or systems in real, and was mainly concerned with forecasting and prediction. The models in this perspective are seen and used as analysis tools, which allow analyzing the conjoint outcome of multiple processes, rather than as predictive crystal balls. This point can be clarified on the example of an airliner pilot training simulator: none of the simulated flights in any flight simulator can exactly replicate a particular flight for a given destination, and this is not the purpose of the flight simulator. The simulator is used to enhance the understanding of the pilot trainee on the interaction of multiple dynamics regarding the plane and the weather conditions. Such a purpose exactly resembles the purpose of model use within the proposed analytical perspective; flight-simulators for socio-technical systems. Despite acknowledging the intrinsic randomness, and non-deterministic nature of some events, introducing those into the models is considered to have the potential to hamper the benefits of such model use, since it would be much harder to trace the source of observed dynamics.

d. Role of case-specific conditions
One of the key assumptions of this study is about the existence of some structural similarity among different socio-technical systems: a search for general understanding presupposes that the set of key elements as well as the way these elements are interrelated show some similarity. Saying that, the importance of unique, case-specific circumstances are not disregarded. Any
Conclusions and Reflections

general conclusion drawn via this analytical perspective should be transferred to specific cases with care, and case-specific circumstances should be taken into account. In some sense, a general understanding provides knowledge about the ways the system may respond to certain events, changes, etc. Therefore, there is still the important task of coupling such general insight with case-specific conditions in order to be able to say something about a particular real socio-technical system’s plausible behaviour.

e. Social dynamics as a vital part of explanation

Differing from most of the former studies on analysis of socio-technical transitions, this study does not solely focus on a particular innovation/novelty, or on techno-physical dynamics: it incorporates social dynamics of equal importance to techno-physical dynamics in explaining the dynamics of a socio-technical system. This can immediately be seen by considering the fundamental building blocks of the actor-option framework. The proposed conceptual representation puts the actor-option interaction to the core of an analysis of transitional change. This makes the actor-option framework one of the approaches that allow analyzing the technology-society interaction (e.g. how they bilaterally shape each other, and how they yield transitional change) in a formalized quantitative manner.

Although the proposed perspective takes social dynamics into account, the complexity of these dynamics are captured only in a limited manner. As stated earlier, the adaptive and reflexive nature of social aspects of the system is the key difficulty in this respect. The depiction used in this framework is only a minimal representation of this complexity. For example, the way social actors are characterized is very simplistic compared to an actual actor’s capabilities. However, we claim that even such a simplified depiction is superior to keeping social aspects out of the analysis due to reasons such as incommensurability, impossibility of formalization and quantification, etc. Saying that, we also recognize this as a direction of future research: enhancing the framework in this respect by improving the depiction of social actors into a more elegant form would be a valuable contribution to the proposed conceptualization.

f. Preliminary state of the mechanism set

We evaluate the proposed set of mechanisms as rich enough in its current form to be used for analyzing transitional change in socio-technical systems. However, this set is not in its ultimate form: the set may be improved in the future by addition of new mechanisms, and refinement/revision of the existing ones. The defining characteristics of the analytical perspective are rooted in the actor/option-based depiction of the system. While preserving these characteristics, the analytical perspective can be improved via refining the mechanism set in the light of new evidence and findings. Reflecting on the current set of mechanisms, it can be said that the most promising direction of improvement is related to the social mechanisms. Especially, an elaboration on the mechanism of preference change can be a very valuable addition to the current state of the proposed mechanism set.

g. Specificity of the proposed mechanisms

The way mechanisms are depicted in the actor-option framework can be considered as not being specific enough, since the framework leaves the task of formal specification and quantification of the mechanisms to the analyst. Depending on the perspective, this can be seen both as a shortcoming, and as a merit. Since it leaves an important gap between conceptualization and implementation, it can be seen as not providing enough guidance. However, the objective of
this study is not to deliver ready-to-explore simulation models. It aims to provide a general perspective and system depiction that can be used for a wide range of systems, and by a wide range of analysts with differing backgrounds. The non-specific depiction of the mechanisms is chosen to assure such a broad coverage. In different systems, manifestations of a certain mechanism may be different in specific details; sticking to a general depiction, it is aimed to cover both manifestations.

Additionally, the choice of presenting mechanisms at a general qualitative level is related to us not taking a strong theoretical stance, especially regarding social, organizational and cognitive processes. For example, depending on the decision theoretical stance taken, a choice process can be specified in various forms, each being equally defendable. Instead of hard-coding a specific theoretical perspective in our models, we chose to allow analysts with different theoretical choices to use our analytical perspective to develop their models according to their theoretical views.

h. Association with key transition concepts
The three levels of the multi-level perspective (i.e. micro, meso, and macro); and niche, regime, and landscape are key concepts in the transition field. We neither use these concepts as integral parts of our approach, nor make explicit associations with them. This is a deliberate choice to avoid any vagueness in the proposed perspective that would be rooted in the definition of these concepts. Despite their wide-scale utilization, it is surprisingly difficult to talk about a clear and agreed upon definition of these key concepts. We chose not to rely on such concepts that can be associated with different things by different scholars.

However, this does not imply any incompatibility of the proposed perspective with these key concepts. A system depiction in terms of actors and options, or an observed model behaviour can be mapped into these concepts; and described/interpreted based on them. This mapping is left to the analysts to use our perspective, and it may naturally differ dependent on the definitions adopted by the analyst.

Most importantly, the actor-option framework is very closely related, and complementary to the conceptual field-interpretation of the regime/niche concepts discussed earlier: the framework is the most comprehensive effort towards filling these fields with the proposed mechanisms, which represent internal change processes.
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Appendix A. The WasteTrans Model

A.1. Overview

The model for the Dutch waste management transition case, i.e. WasteTrans, is a system dynamics model, which is developed using Vensim software. The model covers 3 waste management options (i.e. land-filling, incineration, recycle/re-use), and the behaviour of 4 actor groups (i.e. municipalities, waste contractors, government, opinion groups) with respect to these available waste management options. In the following section, we will introduce the basic model structures and formulations that are used to represent change processes regarding the options, as well as regarding the behaviour of the actors. Besides, the full set of equations, as well as the Vensim model files can be obtained directly from the author, or can be downloaded from [www.gyucel.net/PhD/WasteTrans.htm](http://www.gyucel.net/PhD/WasteTrans.htm).

Following sections introduce the conventions regarding the stock-flow diagrams, which are the visual representations of model structure in system dynamics approach, and the abbreviations used in the WasteTrans model.

A.2. Stock-flow diagrams

In system dynamics, two main building blocks are used in modelling the system of concern. Stocks are briefly accumulating variables that identify the state of the system at a particular time. These stocks are manipulated via instantaneous inflows and outflows, which are referred as flow variables.

A simple system regarding atmospheric CO₂ accumulation is presented in the stock-flow representation form in Figure A.1. In this representation, the stock variable of the system (Atm_CO2) is represented with a rectangular box. The thick arrows with valves pointing to, and emerging from this stock variable represent the flow variables related to this stock. Arrowheads indicate the direction of these flows. According to this representation, inflow to
the stock is emissions by fossil fuel usage (\textit{EmsByFossilFuels}), and outflow from the same stock is the diffusion flow (\textit{CO2} \textit{Diffusion}). In each time period, magnitude of \textit{EmsByFossilFuel} indicates the amount of \( \text{CO}_2 \) added to the atmosphere, whereas \textit{CO2} \textit{Diffusion} represents the amount flowing out of the atmosphere via diffusion to the oceans. Remaining variables in the figure are called \textit{auxiliary} (or converter) variables and they are used for calculation of flows and defining the links between components of the system (e.g. \textit{FossilFuelUsage}). Finally, curved thin arrows indicate causal relation between two variables in the system. In this simple example, the magnitude of \textit{EmsByFossilFuel} is formulated as a product of fossil fuels used (\textit{Fossil_Fuel_Used}) and the average emission rate per fossil fuel usage (\textit{Emissions_Per_Fossil_Used}).

A system dynamics model corresponds to a set of differential or difference equations, in which \textit{stocks} represent state variables and \textit{flows} represent rates of change. The stock-flow representation of the simple \( \text{CO}_2 \) example is given in Figure A.1. Differential equations regarding the same system are also given in Equations A.1 through A.3.

\[
\frac{d\text{Atm CO}_2(t)}{dt} = \text{EmsByFossilFuels}(t) - \text{CO2Diffusion}(t) \tag{A.1}
\]

\[
\text{EmsByFossilFuels}(t) = \text{EmsPerFossilFuel} \times \text{FossilFuelUsage}(t) \tag{A.2}
\]

\[
\text{CO2} \text{ Diff}(t) = \text{Atm CO}_2(t) \times \text{CO2} \text{ Diff Frac} \tag{A.3}
\]

A.3. \textbf{Variable naming convention and abbreviations}

Most of the variable names are constructed in a modular manner. The first part of the name of a variable indicates the \textit{option}, or the \textit{actor}-type to which the variable relates. For example, \textit{Land\_Capacity} is the variable that represents the installed capacity for landfilling. Similarly, \textit{Reg\_Imp\_SoilPoll} is the variable that represents the importance of soil pollution for the regulator actors in the model. The variable names can be interpreted in this manner using the abbreviations given below in Table A.1.
As mentioned earlier, the model covers three major options for waste management; landfilling, incineration, and recycle/re-use. These options are primarily characterized by their performance in soil pollution (i.e. pollutant released to soil per unit of waste processed), air pollution, and space requirements. All these properties are considered as mainly related to the technological nature of the options, and they are modelled to be dynamic. The model structure used for each property of each option is identical, but they only differ in the values of parameters, which determine the dynamics of development. Therefore, we only discuss the structure used for soil pollution performance of the landfilling option as an example. Stock-flow diagram related to the technological development in the soil pollution performance of landfilling is given in Figure A.2.
The best feasible level of the soil pollution performance is represented by the variable `Land_SoilPoll_Per_Waste_Min`. This variable changes over time representing an exogenous property development mechanism. However, an improvement in the best feasible level does not automatically correspond to an improvement in the soil pollution performance of the landfilling practice in the system (`Land_SoilPoll_Per_Waste`) since the existing capacity uses old technology and/or practices. The change in `Land_SoilPoll_Per_Waste` is dependent first of all on the gap between the current performance level, and the best feasible one; i.e. `Land_SoilPoll_Per_Waste_Gap`. Two other factors also influence the rate of development. One of them is the regulatory push, which is represented by the current importance of the soil pollution for the regulator compared to its reference level (i.e. initial level). Second one is the ratio of investment funds allocated to landfilling by providers to the available capacity. A high ratio indicates a higher possibility of technical improvement through new investments. The equations used for the aforementioned option development process are given below:

\[
Opt_{\text{Prop \_ Chg}}(t) = Opt_{\text{Prop \_ Gap}}(t) \times Opt_{\text{Prop \_ Chg \_ Frac}}(t) \quad \text{[A.5]}
\]

\[
Opt_{\text{Prop \_ Gap}}(t) = Opt_{\text{Prop \_ Min}}(t) - Opt_{\text{Prop}}(t) \quad \text{[A.6]}
\]

\[
Opt_{\text{Prop \_ Chg \_ Frac}}(t) = Opt_{\text{Prop \_ Chg \_ Frac \_ Norm}} \times f(t) \times g(t) \quad \text{[A.7]}
\]

\[
f(t) = effectInvToCap\left(\frac{Opt_{\text{InvToCapacity}}(t)}{Opt_{\text{InvToCapacity}}(0)}\right) \quad \text{[A.8]}
\]

\[
g(t) = effectRegImp\left(\frac{RegImp_{\text{Prop}}(t)}{RegImp_{\text{Prop}}(0)}\right) \quad \text{[A.9]}
\]

`effectIncToCap(.)` and `effectRegImp(.)` are table functions (graphical functions) specified using the GRAPH interface of Vensim software, which is used to specify non-linear interactions between variables. These functions are given below.

1 For convenience, Opt (i.e. option) stands for ‘Land’, and Prop (i.e. property) stands for ‘SoilPollPerWaste’ in this particular example.
A.5. Actors

The key model structure in WasteTrans related to the actors is related to their ‘support’ levels for the available options. The concept of ‘support’ corresponds to different things for different actor groups. For the municipalities (i.e. practitioners), the level of support for an option corresponds to the percentage of waste the municipality plans to manage through that option. For the waste contractors (i.e. providers), it corresponds to the percentage of capacity investments to be allocated to the option. For the government (i.e. regulator), it is the target level waste percentage to be managed through the option. The support-shift structures used for the actor groups are structurally identical, and mainly differ in parameter values that represent the possible pace of support shift. Below we discuss the support-shift structure on the example of provider actors (Figure A.5);

The actors are conceptualized as shifting their support between the available options in the model. In doing so, it is assumed that the waste contractors are committed to their former course of investment behaviour, which also includes investments made to replace depreciating capacity. In that respect, they change their investment behaviour in a gradual manner, instead of a radical history-independent manner. According to the used model structure, the change in the investment percentage to incineration, for example, increases by shifting support from the other two options, and decreases by shifting support to the other two options.

\[
\frac{d\text{IncInv\%}(t)}{dt} = s_{\text{Recycle,Inc}}(t) + s_{\text{Land,Inc}}(t) - s_{\text{Inc,Recycle}}(t) - s_{\text{Inc,Land}}(t) \quad \text{[A.10]}
\]

\[
s_{A,B}(t) = \text{Prov_Sup_AToB variable in the stock-flow diagram}
\]

An actor’s shifting of support from one option to another is dependent on how the actor assesses these options; the actor will shift support from the option with relatively lower assessment score to the one with a higher assessment score. Based on this logic, the individual support-shift flows in Figure A.5 are formulated as follows;

\[
s_{A,B}(t) = H(V_B(t) - V_A(t))\gamma(V_B(t) - V_A(t))\text{AInv\%}(t) \quad \text{[A.11]}
\]
According to this formulation, there is a support shift from option A to option B only if
the actor assesses the option B to be superior to the option A. The pace of support shift is
dependent on the difference in the assessment of the options; if the difference of the actor’s
assessments for the options is low, the pace of support shift is also low. Additionally, the shift
of support is proportional to the current level of support for the losing option. \( \gamma \) stands for the
reference level of support shift pace. The key variables in this formulation are the assessment
scores (i.e. \( V_A(t) \)), which will be discussed below.

The actors consider multiple issues, such as their soil and air pollution performance, while
attributing an assessment score to an option. In doing so, a set of weights is used to represent
the relative importance of a certain issue for the actor. Using these weights (i.e. \( \lambda(.) \)), the total
assessment score of an option is calculated as follows;

\[
V_A(t) = \sum_j \lambda_j(t) v(\hat{x}_{A,j})
\]  

[A.13]

\( \hat{x}_{i,j} \) is the relative performance of the option \( i \) (e.g. landfilling) in the issue \( j \) (e.g. soil pollution),
and this is calculated by comparing the performance of an option with the best performance
among the available options (Equation A.14). It is important to note that, since it is the relative
performance of an option that matters, an option’s assessment by the actors may worsen if the
best available performance in an issue improves.

\[
\hat{x}_{A,j} = \frac{x_{A,j}}{\min_i(x_{i,j})}, \quad i = A, B, C, ...
\]  

[A.14]

\( v(.) \) is the component value function, which converts the relative performance of an option
with regard to an issue into a scalar value in the range of \([0,5] \). If the option performs best in an
issue, the component value function returns 5. If the option is performing very poorly compared
to the best performance available it is attributed 0. The component value function incorporates
a level of status quo-seeking tendency, since the value attributed to an option starts decreasing
only when it performs significantly worse than the best option. Even when a better option is
available for the actor, the actor has a tendency to value this new option and the actor’s current
choice very closely, as long as the new one does not outperform the current choice of the actor.

The importance of the issues for the actors (i.e. \( \lambda(.) \)) is also time-dependent in the model.
Figure A.7 provides a sample structure for demonstrating the way importance of an issue is
changing in the model for an actor. The selected case is about the importance of air pollution

\[
H(x) = \begin{cases} 
1 & \text{if } x \geq 0 \\
0 & \text{otherwise}
\end{cases}
\]  

[A.12]
issue for the practitioner-type of actors. The driver of change is the recent air pollutant emission level relative to what it was in the past (i.e. AirPollEmissions_Rel). However, an increase in the emission levels does not induce an immediate jump in the importance of the air pollution issue for the actors. First of all, internalization of the problem, and reflecting it to the preferences of the actor is assumed to take some time for the actors. Therefore, an increase in the emissions yields a change in the importance of the issue (i.e. Pract_Imp_AirPoll) in a gradual manner, and after an importance change delay. The equation formulations used for the importance change process are given in Equations A.15 through A.17.

\[
\frac{d\text{ImpAirPoll}(t)}{dt} = \frac{\text{ImpAirPoll}_{\text{Des}}(t) - \text{ImpAirPoll}(t - dt)}{\text{Imp}_{\text{Chg}\_\text{Del}}}
\]  
\[\text{A.15}\]

\[
\text{ImpAirPoll}_{\text{Des}}(t) = \text{ImpAirPoll}_{\text{Ini}} \times \text{ImpAirPoll}_{\text{DesFact}}(t)
\]  
\[\text{A.16}\]

\[
\text{ImpAirPoll}_{\text{DesFact}}(t) = h\left(\frac{\text{AirPoll}_{\text{Emissions}}(t)}{\text{AirPoll}_{\text{Emissions}}(0)}\right)
\]  
\[\text{A.17}\]

A.6. Overall system performance

The waste allocation decisions of the municipalities are the primary drivers of waste-related pollution performance of the Dutch system in the model. The total amount of waste to be handled by the municipalities is introduced as an exogenous, time-dependent variable to the model. It is assumed that the waste generation will follow the pattern observed during the 1985-2003 period. The following function, which is calibrated in order to get the best fit to the 1985-2003 data series, is used to represent the total waste generation (in megatons);

\[
\text{Waste Generated}(t) = 31.821 + 0.9593t
\]  
\[\text{A.18}\]

The municipalities’ allocation of this total waste to the available options determines the amount of waste generated via each waste management option. The dynamics of pollution levels are represented with very simple structures that represent the basic accumulation and decay dynamics related to pollutants in the model. For the soil pollution case (Figure A.8), the amount of pollutants released to soil (i.e. SoilPollInflow) is the sum of pollutants from waste managed through all three options. The decay of the pollutants in the soil is represented with a second-order material delay structure. Following the release of pollutants to the soil in their original form, the first decay process represents the processes such as leaching and diffusion of the pollutants into the soil. In other words, pollutants change form, but still in the system. The decay of this latter form of pollutants correspond to the second outflow in the given stock-flow diagram (i.e. SoilPoll2_Diff).
A very similar stock-flow structure is used for the air pollution case (Figure A.9). Total emission is the result of emissions caused via each waste management option, which is determined by the total amount of waste managed via the option and the air pollution emitted per unit amount of waste. Differing from the soil pollution case, air pollution diffuses much faster when it is considered at the regional level. Due to trans-boundary atmospheric flows, the air pollution levels experienced regionally in the Netherlands can fall much faster compared to the decay of soil pollutants. Additionally, transformation of the air pollutants into a second form as in the case of leaching of soil pollutants is not considered. In that respect, a first-order material delay structure is used to capture the probable dynamics of aggregate regional air pollution levels.

A.7. Sensitivity runs

A set of extensive sensitivity runs have been conducted in order to evaluate the robustness of the simulated system behaviour to changes in some uncertain variables. These sensitivity runs are conducted using the integral sensitivity analysis features of the Vensim software. Briefly, the analysis is conducted as follows;

- A set of variables whose initial values carry some level of uncertainty is identified
- Plausible value ranges are defined for each variable
- In each sensitivity run, variables are initialized according to a value randomly sampled from their plausible ranges. Uniform distributions are used in sampling. Although
the sampling is done independently for each variable, the consistency of the sampled variables with the qualitative data is preserved. For example, *space* was a more important issue for the government in ‘70s than the *air pollution*. Therefore, in the sensitivity runs, the initial importance of *air pollution* cannot be higher than the *space* issue. This is what is meant by ‘preserving the consistency with the qualitative information’.

- The model is initialized using these randomly sampled values, and it is run.
- The procedure is repeated 1000 times.
- The resulting 1000 output curves are summarized in a single graph, which shows behaviour envelopes. For example, 50% envelope indicates that 500 of the simulations resulted in a behaviour curve that resides in that envelope.

### a. Sensitivity to initial importance values

In this experiment the selected set of variables are related to the initial values for the importance of different issues for the regulator actor. The selected variables, and the plausible ranges for these variables are given in Table A.2. The results of the sensitivity runs are given in Figure A.10 and A.11, which show percentage of waste managed through landfilling and incineration, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Base</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg_Imp_AirPoll_Ini</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Reg_Imp_PubSup_Ini</td>
<td>1.5</td>
<td>0.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Reg_Imp_SoilPoll_Ini</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Reg_Imp_Space_Ini</td>
<td>2</td>
<td>1.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table A.2. Parameter ranges in the sensitivity run

![Figure A.10. Share of landfilling in the sensitivity run](image1)

![Figure A.11. Share of incineration in the sensitivity run](image2)

### b. Sensitivity to pace of priority change process

In this experiment the selected set of variables are related to the time it takes for the actors to update their preference (i.e. alter the importance of an issue). The selected variables, and the plausible ranges for these variables are given in Table A.3. The results of the sensitivity runs are given in Figure A.12 and A.13, which show percentage of waste managed through landfilling and incineration, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Base</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pract_Imp_Chg_Del</td>
<td>10</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Reg_Imp_Chg_Del</td>
<td>7</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Pub_Imp_Chg_Del</td>
<td>7</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>

Table A.3. Parameter ranges in the sensitivity run
c. Sensitivity to air pollution performance of the options

In this experiment the selected set of variables are related to the initial values for the air pollution performance of the options (i.e. pollutant emitted per Mton waste processed). The selected variables, and the plausible ranges for these variables are given in Table A.4. The results of the sensitivity runs are given in Figure A.14 and A.15, which show percentage of waste managed through landfilling and incineration, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Base</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land_AirPoll_Per_Waste_Ini</td>
<td>0.6</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Inc_AirPoll_Per_Waste_Ini</td>
<td>3.0</td>
<td>0.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Recycle_AirPoll_Per_Waste_Ini</td>
<td>0.2</td>
<td>0.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Figure A.12. Share of landfilling in the sensitivity run

Figure A.13. Share of incineration in the sensitivity run

Figure A.14. Share of landfilling in the sensitivity run

Figure A.15. Share of incineration in the sensitivity run
Appendix B. The NavalTrans Model

B.1. Overview

NavalTrans is an agent-based model, and it is developed on Eclipse, an open-source integrated development environment (IDE), using Repast J agent modelling toolkit. An instance of the model is composed of two main components; the model code, and the parameter file. The model code depicts the actions of the actors, relations between system elements, and general developments in the system. In other words, it depicts the structure of the model. The parameter file is a conventional MS Excel file, which contains the initial values of the model parameters that are needed to create an instance of the model. This architecture brings ease and flexibility to experimentation with NavalTrans: no programming skills are required in order to create different instances of the model and conduct experiments, since creating a new parameter file suffices for the task.

The model covers 2 naval transportation options (i.e. wind-powered sail-ships, and steam-powered steam-ships), and the behaviour of 9 actor groups. 7 of these groups are practitioner/user type of actors that constitute the demand-side of the transportation system. The remaining two actor groups represent the provision side of the system; i.e. provider-type actors.

In the following section, we will first introduce the objects, which are the basic pieces of the model. Following that, the behaviour of the overall model, as well as the objects will be discussed mainly using pseudocodes\(^1\). When necessary, implemented functional relationships will be introduced in detail. Besides, the full model code, as well as the parameter file used for the reference simulations can be obtained directly from the author, or be downloaded from www.gyucel.net/PhD/NavalTrans.html.

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\(^1\) Pseudocode is a compact and informal high-level description of a computer programming algorithm that uses the structural conventions of a programming language, but is intended for human reading rather than machine reading.
B.2. Object classes

Before directly going into the model discussion, some basic notions related to object-oriented programming, and naturally to agent-based modelling, are introduced below. Objects are the fundamental elements of an object-oriented program, and they can be considered as distinct pieces of software that have a state description, and a set of methods that depict the behaviour of the object. An object stores its state in fields (variables in some programming languages) and exposes its behaviour through methods (functions in some programming languages). Methods operate on an object's internal state and serve as the primary mechanism for object-to-object interaction. In an agent-based model, which is a special type of object-oriented program, each individual agent in the model can be considered as an object, for example. However, there may be other objects that are not agents, which are needed for the functioning of the overall model.

A class corresponds to a general representation of a particular type of object. In other words, it is the blueprint from which individual objects are created in the program. Every object in the program is said to be an instance of a particular class. In an agent-based model, there may be numerous consumer-agents. Each of these agents is an object in the model, and the general description of a consumer is the consumer class.

In NavalTrans there are 6 object classes. 4 of these classes directly correspond to the concepts from the actor-option framework; option, actor, practitioner, and provider classes. The other two classes are more operational, and are related to the functioning of the overall model; model and oracle classes. We start with introducing these latter two classes, and then we will introduce the others.

a. Controller class

The controller class is the main controller of NavalTrans. First of all, the controller is responsible for creating an instance of NavalTrans. This involves initialization of the agents based on the parameter file being used, and setting the simulation run length. Secondly, the controller also controls the simulation schedule during a simulation run. The simulation schedule is related to the order in which different agents will be activated to perform their tasks in every simulation step. Finally, the controller class is also responsible for collecting data from agents during a simulation run, and displaying this data in the form of display surfaces and time-series plots.

There is only one instance of this class in NavalTrans.

b. Oracle class

As the name implies, the oracle class is related to information; it is the object that knows everything when NavalTrans is to be initialized. This class establishes the link between the model file and the parameter file. While initializing a particular instance of NavalTrans, the oracle reads the values of the model parameters from the parameter file, and reports these to the model object.

This class uses Apache POI HSSF libraries for reading data from MS Excel files.

There is only one instance of this class in NavalTrans.
c. **Option class**
The option class in NavalTrans corresponds to the naval transportation options considered in the case study. This class describes the way an option will be represented in the model (i.e. variables), as well as the mechanisms that alter the properties of the options (i.e. methods).

The basic set of variables of the option class is as follows:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>attrAct[i]</td>
<td>Actual level for the attribute i</td>
</tr>
<tr>
<td>attrBase[i]</td>
<td>Initial (base) level for the attribute i</td>
</tr>
<tr>
<td>attrBest[i]</td>
<td>Technically feasible best level for the attribute i</td>
</tr>
<tr>
<td>attrEconScale[i]</td>
<td>Whether the attribute i is influenced by economies-of-scale, or not</td>
</tr>
<tr>
<td>attrTechDevFracNorm[i]</td>
<td>Reference value of technical development fraction for the attribute i</td>
</tr>
<tr>
<td>attrType[i]</td>
<td>Type of the attribute i; indicates what type of development mechanism is active on the attribute i</td>
</tr>
<tr>
<td>capaTotal</td>
<td>Option's total vessel capacity</td>
</tr>
<tr>
<td>scale</td>
<td>Option's recent scale of utilization</td>
</tr>
</tbody>
</table>

The basic set of methods of the option class is as follows:

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>attrUpdate(.)</td>
<td>Updates the attribute values of the option</td>
</tr>
<tr>
<td>updateStat(.)</td>
<td>Updates the statistics related to the option, such as utilization level, capacity-demand balance, etc.</td>
</tr>
</tbody>
</table>

There are two instances of the class in NavalTrans; sail-ship option, and steam-ship option.

**d. Actor class**
The actor class defines social actors in general. Independent of being a demand-side, or supply-side actor, the social actors share some basic characteristics in the way they are conceptualized for this model. The actor class corresponds to this general description of a social actor.

The basic set of variables of the actor class is as follows:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>attrPerc[opt][prop^1]</td>
<td>The perceived level of the attribute prop of the option opt</td>
</tr>
<tr>
<td>attrPerDelay</td>
<td>Attribute perception delay of the actor</td>
</tr>
<tr>
<td>optScoreFunc</td>
<td>Component value function</td>
</tr>
<tr>
<td>prior[objc]</td>
<td>Priority of the objective objc</td>
</tr>
<tr>
<td>resource</td>
<td>Total amount of resources controlled by the actor</td>
</tr>
<tr>
<td>resToOpt[opt]</td>
<td>Resources allocated to the option opt</td>
</tr>
<tr>
<td>suppor[opt]</td>
<td>Support of the actor to option opt</td>
</tr>
<tr>
<td>supShiftNormal</td>
<td>Actor’s reference rate of support shift</td>
</tr>
</tbody>
</table>

The basic set of methods of the actor class is as follows;

---
2 The basic set includes the mechanism related to the behavior of the agents in the socio-technical context. The methods related to the functioning of the program, such as the ones related inter-object communication, data sorting, etc. are not discussed within the set of basic method for the sake of clarity.

---
e. **Practitioner** class

The practitioner class is a subclass of the actor class. In other words, a practitioner is a special type of actor. It inherits all the variables and methods from the actor class, and on top of those it has some others that differentiate it from other subclasses. As the name implies, the practitioner class corresponds to the demand-side agents in the *NavalTrans* model.

The basic set of variables of the practitioner class is as follows:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>noSubType</td>
<td>Number of different groups of practitioners to be introduces</td>
</tr>
<tr>
<td>scaleShare[subType]</td>
<td>The share of each practitioner group in the transportation market</td>
</tr>
<tr>
<td>resGrowthPerc</td>
<td>Growth percentage for practitioner resources</td>
</tr>
<tr>
<td>resToProv[prov][opt]</td>
<td>Resources allocated to provider prov for transportation via option opt</td>
</tr>
</tbody>
</table>

The basic set of methods of the practitioner class is as follows:

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>supportUpdate(.)</td>
<td>Update the actor's support for different options</td>
</tr>
<tr>
<td>allocateRes(.)</td>
<td>Allocate resources to existing providers and options</td>
</tr>
</tbody>
</table>

There are 500 instances of the class in *NavalTrans*. In other words, there are 500 practitioner agents in the model. The distribution of these agents according to the sub-types is given on the right.

<table>
<thead>
<tr>
<th>Practitioners/Users</th>
<th># of agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merchant – Type I</td>
<td>50</td>
</tr>
<tr>
<td>Merchant – Type II</td>
<td>50</td>
</tr>
<tr>
<td>Merchant – Type III</td>
<td>50</td>
</tr>
<tr>
<td>Merchant – Type IV</td>
<td>50</td>
</tr>
<tr>
<td>Government Postal Service</td>
<td>50</td>
</tr>
<tr>
<td>Luxury Passengers</td>
<td>50</td>
</tr>
<tr>
<td>Emigrants</td>
<td>200</td>
</tr>
</tbody>
</table>

f. **Provider** class

Similar to the practitioner class, the provider class is also a subclass of the actor class, and inherits its variables and methods. This class corresponds to the supply-side agents in *NavalTrans*.

The basic set of variables of the provider class is as follows:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>capacity[opt]</td>
<td>Total option opt capacity controlled by the agent</td>
</tr>
<tr>
<td>capaInv[opt]</td>
<td>Capacity investment to option opt</td>
</tr>
<tr>
<td>capaLoss[opt]</td>
<td>Capacity loss in option opt due to depreciation</td>
</tr>
<tr>
<td>resFromPrac[pract][opt]</td>
<td>Resources received from practitioner pract related to option opt</td>
</tr>
</tbody>
</table>
The basic set of methods of the provider class is as follows:

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>supportUpdate(.)</td>
<td>Update the actor’s support for different options</td>
</tr>
<tr>
<td>updateCapacity(.)</td>
<td>Update the total capacity controlled by the agent related to each option</td>
</tr>
<tr>
<td>updateCapaFree(.)</td>
<td>Update the unused freight capacity after processing the requests of the practitioner agents</td>
</tr>
<tr>
<td>updateResFromOpt(.)</td>
<td>Update resources received from practitioners for each option</td>
</tr>
</tbody>
</table>

There are 200 instances of the class in NavalTrans; i.e. 200 provider. The distribution of these agents according to the sub-types is given on the right.

<table>
<thead>
<tr>
<th>Providers</th>
<th>#of agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual Owners</td>
<td>150</td>
</tr>
<tr>
<td>Large Shipping Comp</td>
<td>50</td>
</tr>
</tbody>
</table>

B.3. **Pseudocode of NavalTrans**

The action flow in NavalTrans during a simulation run is presented by the following pseudocode. The individual actions mentioned in this pseudocode are explained in the following section.

```
Initialize the model instance {
    Read the parameter file for parameter values
    Create N_{prac} number of practitioners
    Create N_{prov} number of providers
    Create N_{opt} number of options
}
Repeat until the time step is equal to the simulation final time {
    Repeat until all practitioners are considered {
        Randomly pick one practitioner agent
        Ask the agent to perform the following {
            Assess the available options (valueDecision)
            Update perceived information (attrPercUpdate)
            Update utilization of the options (supportUpdate)
            Allocate resources to the options (allocateRes)
        }
    }
    Repeat until all providers are considered {
        Randomly pick one provider agent
        Ask the agent to perform the following {
            Assess the available options (valueDecision)
            Update perceived information (attrPercUpdate)
            Update the demand received (updateResFromOpt)
            Update investment for the options (supportUpdate)
        }
    }
    Repeat until all options are considered {
        Randomly pick one option
        Ask the object to perform the following {
            Update the option properties (attrUpdate)
            Update the statistic (updateStat)
        }
    }
}
End simulation
```
B.4. Description of the agent actions

a. Practitioner actions

i. `valueDecision(.)`
Calculates a preliminary assessment value for all options by calculating a weighted average of its properties, as the actor knows them;

\[
valueDecPrel_{\text{opt}} = \sum_{\text{obj}} \text{prior}_{\text{obj}} \times \text{attrPerc}_{\text{opt, obj}}
\]  
[B.1]

Then these preliminary assessment values are normalized based on the best option in the system according to the agent;

\[
valueDec_{\text{best}} = \max_{\text{opt}} (valueDecPrel_{\text{opt}})
\]  
[B.2]

\[
valueDec_{\text{opt}} = \frac{valueDecPrel_{\text{opt}}}{valueDec_{\text{best}}}
\]  
[B.3]

ii. `attrPercUpdate(.)`
It is assumed that the learning takes place mainly through exogenous information sources, and the pace of learning is proportional to the imperfection in the actor’s perception about a certain property of an option. According to this assumption, the perception of an actor regarding each property of each option is updated as follow;

\[
attrPerc_{\text{opt, prop}}(\text{step}) = attrPerc_{\text{opt, prop}}(\text{step} - 1) + correctionTerm(\text{step})
\]  
[B.4]

\[
correctionTerm(\text{step}) = \frac{attrAct_{\text{opt, prop}}(\text{step}) - attrPerc_{\text{opt, prop}}(\text{step})}{attrPercDelay}
\]  
[B.5]

where \(\text{step}\) stands for the iteration step (or time-step) of the simulation.

iii. `supportUpdate(.)`
In NavalTrans, the `support` concept represents how much (in terms of percentages) of its freight a merchant wishes to transport via a certain option, or which portion of an emigrant group wishes to travel via a certain option, as already discusses in Chapter 9. Based on this interpretation, an increase in the support for an option means a decrease in the support of the other. The change in the actor’s support for an option is formulated as follows;

\[
sup\text{Shift}_{\text{opt1, opt2}} = A \quad \text{if} \quad valueDec_{\text{opt1}} > valueDec_{\text{opt2}}
\]  
[B.6]

\[
A = (valueDec_{\text{opt1}} - valueDec_{\text{opt2}}) \times sup\text{ShiftNorm} \times support_{\text{opt2}}
\]  
[B.7]

\[
support_{\text{opt1}}(\text{step}) = support_{\text{opt1}}(\text{step} - 1) + sup\text{Shift}_{\text{opt1, opt2}}
\]  
[B.8]
iv. **allocateRes(.)**

Allocation of resources corresponds to allocation of the freight that needs to be transported to the available ships according to the current support levels of the actor (i.e. desired allocation of freight among transportation options), in the case of a merchant. In that respect, the workflow in this method is given in the following pseudocode;

Repeat for each option {
  Calculate the freight aimed to be transported using the option (resDes)
  Repeat until either all freight is assigned, or all providers are considered {
    Randomly select a provider agent
    Ask for the free capacity controlled by the provider
    Assign freight to the provider according to the free capacity
    Ask the provider agent to update the free capacity it controls
    Update the amount of freight that needs to be transported
  }
  If there is still some unassigned freight, register it as surplus
}

If the surplus for an option is positive, this indicates that the actor could not find enough free capacity in order to realize the desired allocation of the freight among available options. For example, a merchant might have wanted to ship 50 tons via steam-ships. However, if the agent can only find free capacity for 30 tons on the steam-ships available in the market, then the surplus for steam-ship option will be 20 tons this practitioner agent. If this is the case, the agent tries to ship its freight through the other option. In this particular example, the merchant looks for free capacity of 20 tons on sail-ships.

Repeat for each option{
  Allocate the surplus to the other option
  If there is still some surplus, register the surplus as failed shipment
}

b. **Provider actions**

i. **valueDecision(.)**

The action is identical to the one discussed above for the practitioner agents.

ii. **attrPercUpdate(.)**

The action is identical to the one discussed above for the practitioner agents.

iii. **updateResFromOpt(.)**

The provider agent registers the total demand received from the practitioner agents for each type of ship the provider operates. For the provider with the index prov, the calculation is performed as follow;

\[
resFromOpt_{opt} = \sum_{pract=1}^{N_{pract}} resToOpt_{pract, prov, opt} \text{ for } opt = \{\text{sail, steam}\} \tag{B.9}
\]

3 The practitioner first randomly selects among the providers with whom it did business in the past, and then starts randomly picking out of remaining providers.
iv. \texttt{supportUpdate(.)}

In NavalTrans, the support concept represents how much (in terms of percentages) of its capacity investment resources a ship-owner wishes to allocate to a certain option (e.g. how many of the newly ordered ships will be sail-ships?). The formulation used for representing changes in this support allocation is identical to the formulation given in Equations B.6 through B.8.

Once the new support levels are determined, the provider agent calls for the \texttt{updateCapacity(.)} method. This method updates the shipping capacity controlled by the provider agent in both options. The method works as follow;

\begin{equation}
resTotal = \sum_{opt=\{sail,steam\}} resFromOpt_{opt}
\end{equation}

\begin{equation}
capaInvTotal = capaInvFrac \times resTotal
\end{equation}

repeat for each option{
\begin{equation}
capaLoss_{opt} = \frac{capaTotal_{opt}}{capaLife_{opt}}
\end{equation}

\begin{equation}
capaInv_{opt} = capaInvTotal \times support_{opt}
\end{equation}

\begin{equation}
capaTotal_{opt}(step) = capaTotal_{opt}(step-1) + capaInv_{opt} - capaLoss_{opt}
\end{equation}

}

c. \textbf{Option actions}

i. \texttt{attrUpdate(.)}

The method updates the properties (i.e. attributes) of the options.

\begin{equation}
attrDevFrac_{prop} = attrDevFracNorm_{prop} \times eff_1 \times eff_2
\end{equation}

where \( eff_1 \) stands for the effect of investment flows on attribute development, and \( eff_2 \) stands for the effect of market-share loss on attribute development (related to 'fight-back' or 'sail-ship' effect)

\begin{equation}
\text{eff}_1 = f(\frac{\text{capaInvFracAvg}}{\text{capaInvFracRef}})
\end{equation}

\text{capaInvFracAvg} is the ratio of total capacity investments made for an option in a decision round to the existing total capacity of the option in the market. \text{capaInvFracRef} is the investment fraction that is required to compensate the capacity loss due to depreciations. The function \( f(.) \) is given in Figure B.1.
$\text{eff}_2 = g\left( \frac{\text{supPractChgAvg}}{\text{supPractChgRef}} \right)$ \hfill \text{[B.17]}

where $\text{supPractChgAvg}$ is the average change in the support (i.e. demand) for the option in the market, and $\text{supPractChgRef}$ is the reference value for that, which can be considered as normal. In the base version of the model a 2% market share loss is considered as acceptable (i.e. $\text{supPractChgRef}=-0.02$). The function $g(.)$ is given in Figure B.2.

Using the $\text{attrDevFrac}$ calculated in this way, the new level of the attribute is calculated as follows;

$$\text{attr}_{prop}(\text{step}) = \left( \text{attr}_{best\text{prop}} - \text{attr}_{prop}(\text{step}-1) \right) \text{attrDevFrac} \quad \text{[B.18]}$$

\textit{ii. updateStat(.)}

This method calculates statistics about the whole market for the option by collecting demand-side data from individual practitioners, and supply-side data from individual providers. The method works as follows;

Repeat for every practitioner agent{
    Get the following information from the practitioner agent{
    Assessment score of the agent for the option
    The demand that the agent wanted to transport via the option
    The demand that the agent actually could transport via the option
    Total demand of the agent
    }
}

Repeat for every provider agent{
    Get the following information from the provider agent{
    Vessel capacity controlled by the agent
    Total investment resources of the agent
    Capacity investments of the agent for the option
    }
}
Using the collected information, the method calculates market-level indicators such as average assessment score for the option, average investment fraction to an option, demand-supply balance in the market, etc.

**B.5. Parameter file**

The parameter file consists of three sections corresponding to the *practitioner* agents, *provider* agents, and the *options*. Figure B.3 through B.5 are examples of these sections from a parameter file used for one of the experiments. A new *provider* or *practitioner* type can be added to the model just by adding the corresponding rows to the parameter file. Same holds for introducing a new *option* to the model. *Disp_Factor_XX* columns in the *practitioner* and *provider* sections are related to the dispersion of the agents in the related issue. For example, a high *Disp_Factor_Res* indicates that the model will create agents highly heterogeneous in terms of the amount of resources they control. If the factor is set to 0, all agents will be initialized identical.

**Section of the parameter file related to the options**

<table>
<thead>
<tr>
<th></th>
<th>Base</th>
<th>Speed</th>
<th>Opr. Cost</th>
<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail-ship</td>
<td>0.66</td>
<td>0.66</td>
<td>2</td>
<td>1.33</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Steam-ship</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Best</th>
<th>Speed</th>
<th>Opr. Cost</th>
<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail-ship</td>
<td>0.66</td>
<td>0.66</td>
<td>3.5</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Steam-ship</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Scale</th>
<th>CapaLife</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail-ship</td>
<td>3700</td>
<td>20</td>
</tr>
<tr>
<td>Steam-ship</td>
<td>150</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Speed</th>
<th>Opr. Cost</th>
<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>EconScale</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
### Section of the parameter file related to the practitioners

<table>
<thead>
<tr>
<th>Priorities</th>
<th>Reg</th>
<th>Speed</th>
<th>Opr. Cost</th>
<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR-LV Merchant</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>4.5</td>
<td>0</td>
</tr>
<tr>
<td>LR-HV Merchant</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>4.5</td>
<td>0</td>
</tr>
<tr>
<td>SR-LV Merchant</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SR_HV Merchant</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mail</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Luxury Passenger</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Immigrants</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attr Perc Sail</th>
<th>Reg</th>
<th>Speed</th>
<th>Opr. Cost</th>
<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR-LV Merchant</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0.95</td>
</tr>
<tr>
<td>LR-HV Merchant</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>SR-LV Merchant</td>
<td>1</td>
<td>1</td>
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<table>
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<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
<th>Support</th>
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<td>0.01</td>
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<td>2</td>
<td>1.5</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>2</td>
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</tr>
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<td>0</td>
<td>0</td>
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### Appendix B

#### Section of the parameter file related to the providers

<table>
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<th>Priorities</th>
<th>Reg</th>
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<th>Opr. Cost</th>
<th>Inv. Cost</th>
<th>Range</th>
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<th>Range</th>
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<th>Support</th>
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<th>Reg</th>
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<th>Inv. Cost</th>
<th>Range</th>
<th>Demand</th>
<th>Support</th>
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<th>Disp Factor Attr</th>
<th>Disp Factor Prior</th>
<th>Disp Factor Perc Del</th>
<th>Disp Factor Sup</th>
<th>Attr PercDelay</th>
<th>SupShift Norm</th>
<th>Capa Avg</th>
<th>Capa InvFrac</th>
<th>Capa UtilFrac</th>
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</tr>
</tbody>
</table>
Appendix C. The *ElectTrans* Model

C.1. Overview

*ElectTrans* is an agent-based model, and it is developed on *Eclipse*, an open-source integrated development environment (IDE), using *Repast J* agent modelling toolkit. An instance of the model is composed of two main components: the *model code*, *parameter file* and the *scenario file*. As in the case of *NavalTrans* discussed in Appendix B, the *model code* depicts the actions of the actors, relations between system elements, and general developments in the system. In other words, it depicts the structure of the model. The *parameter file* is a conventional MS Excel file, which contains the initial values of the model parameters that are needed to create an instance of the model. The *scenario file*, as the name implies, includes parameter values, and exogenous time-series data that characterize the scenario context of a simulation.

It its base version *ElectTrans* covers 16 alternative electricity power sources (2 grid-based, and 14 distributed) for the end-users, and 26 alternative electricity generation options that can be used by electricity generation companies to feed the central grid. These technologies can be seen in the parameter files of the base version, which is given in one of the following sections. On the demand-side four types of actors are defined in *ElectTrans*; industrial users, agricultural users, commercial users, and residential users. The supply-side is represented by agents corresponding to the electricity generation companies.

Although these are the figures related to the base version of the model, which is discussed in Chapter 10, neither number of actor types, nor the number of technologies is hard-coded in *ElectTrans*. *ElectTrans* is designed to offer a highly flexible model structure. In that respect, by simply making related changes in the parameter file, the technology coverage of the model can be extended (e.g. to cover 50 technologies). Or, the actor types to be included in the model, as well as the number of agents from each type can be defined on the parameter file. In short, shifting *ElectTrans* from a very aggregate model (e.g. one supply-side generator, one aggregate end-user) to a very disaggregated model (e.g. 10s of generation companies, 1000s of
end-users) can be done just by adding some extra data to parameter file, without any need for changing the model code. This flexibility allows the analyst to shift between different versions of the model quite easily and fast.

In the following section, we will first introduce the objects of ElectTrans. Following that, the behaviour of the overall model, as well as the objects will be discussed mainly using pseudocodes\(^1\). When necessary, implemented functional relationships will be introduced in detail. Besides, the full model code, as well as the parameter files used for the reference and scenario simulations can be obtained directly from the author, or be downloaded from [www.gyucel.net/PhD/ElectTrans.html](http://www.gyucel.net/PhD/ElectTrans.html).

C.2. Object classes

a. Controller class
The controller class is the main controller of ElectTrans. First of all, the controller is responsible for creating an instance of the model. This involves initialization of the agents based on the parameter file being used, setting up the simulation context based on the scenario file, and setting the simulation run length. Secondly, the controller also controls the simulation schedule during a simulation run. The simulation schedule is related to the order in which different agents will be activated to perform their tasks in every simulation step. Finally, the controller class is also responsible for collecting data from agents during a simulation run, and displaying this data in the form of display surfaces and time-series plots.

b. ParamReader class
This class establishes the link between the model and the parameter file. While initializing a particular instance of ElectTrans, an instance of ParamReader class reads the values of the model parameters from the parameter file, and reports these to the model object.

This class uses Apache POI HSSF libraries for reading data from MS Excel files.

c. ScrReader class
ScrReader is very similar to ParamReader in function. ScrReader is developed to read data from the scenario files. While ParamReader reads data just once before a simulation run, ScrReader continues reading data even during a simulation run for time-dependent scenario variables, such as fuel prices.

This class also uses Apache POI HSSF libraries for reading data from MS Excel files.

d. Practitioner class
The Practitioner class depicts the demand-side agents (i.e. end-users of electricity power) of ElectTrans. A practitioner is represented by its power demand, preference structure, and the distributed generation capacity it owns. The power demand of a practitioner agent is specified in multiple periods in a year. In other words, rather than a single aggregate level, the demand is represented in the form of a temporal load profile of the agent, which also shows the fluctuations in the demand of the agent during a year.

---

1 Pseudocode is a compact and informal high-level description of a computer programming algorithm that uses the structural conventions of a programming language, but is intended for human reading rather than machine reading.
The basic set of variables of the Practitioner class is as follows;

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>demand[per]</td>
<td>Power demand of the agent in time period p</td>
</tr>
<tr>
<td>demandGrowthPerctAvg</td>
<td>Average growth percentage of the agent's power demand</td>
</tr>
<tr>
<td>genCapaList</td>
<td>List of distributed generation facilities that is owned by the actor</td>
</tr>
<tr>
<td>learningDelay</td>
<td>Average delay for the actor to learn about external developments</td>
</tr>
<tr>
<td>objectiveWeight[obj]</td>
<td>Weight of the objective obj in the preference structure of the agent</td>
</tr>
<tr>
<td>optInfoList</td>
<td>List of power supply options that the actor considers as feasible for its needs</td>
</tr>
<tr>
<td>supplyToGrid</td>
<td>Binary variable that indicated whether the agent is allowed to feed electricity back to the grid, or not</td>
</tr>
<tr>
<td>type</td>
<td>Type of the agents (industrial, commercial, agricultural, or residential)</td>
</tr>
</tbody>
</table>

The basic set of methods\(^2\) of the Practitioner class is as follows;

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>allocateDemand</td>
<td>Allocates the electricity demand of the agent for a particular period to available supply options (e.g. grid, self-generation, etc.) and updates supply figures</td>
</tr>
<tr>
<td>calculateCostOfElect</td>
<td>Returns the unit electricity supply cost (Euro/kWh) of an option, based on the information known to the agent</td>
</tr>
<tr>
<td>calculateOptUtils</td>
<td>Calculates the expected utility for each electricity supply option feasible/viable to the agent considering multiple objectives of the agent</td>
</tr>
<tr>
<td>getFreeDemand</td>
<td>Returns the portion of the electricity demand of the agent that will be 'liquid' (i.e. demand not tied to any generation capacity or supply-contract) in the beginning of the next period.</td>
</tr>
<tr>
<td>planCapaForFreeDemand</td>
<td>Plans new supply contracts (for grid) or new generation capacity for the liquid part of the demand (i.e. freeDemand)</td>
</tr>
<tr>
<td>updateDemand</td>
<td>Updates the energy demand of the agent for each demand period, and also updates the total yearly demand</td>
</tr>
<tr>
<td>updateGenCapa</td>
<td>Updates the capacity of each generation option under the possession of the agent</td>
</tr>
<tr>
<td>updateMarketInfo</td>
<td>Updates what is known to the agent regarding the market situation (e.g. self-generation popularity, etc.)</td>
</tr>
<tr>
<td>updateOptInfo</td>
<td>Updates the information known to the agent regarding the feasible/considered energy supply options</td>
</tr>
</tbody>
</table>

There are 400 instances of this class in ElectTrans corresponding to end-user agents of four different types; i.e. industrial, agricultural, commercial, and residential.

\( e. \) Provider class

The Provider class represents the supply-side agents, which are the electricity generation companies in the context of ElectTrans. Briefly, a provider is characterized by its preference

\(^2\) The basic set includes the mechanism related to the behavior of the agents in the socio-technical context. The methods related to the functioning of the program, such as the ones related inter-object communication, data sorting, etc. are not discussed within the set of basic method for the sake of clarity.
structure, and the park of generation facilities it operates. These agents are mainly responsible operating their generators, and make capacity-related decisions like investing in new generation facilities and decommissioning the old ones.

The basic set of variables of the *Provider* class is as follows;

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>genList</td>
<td>List of generation facilities owned by the agent</td>
</tr>
<tr>
<td>optInfoList</td>
<td>List of power generation options that the actor considers as feasible for investment</td>
</tr>
<tr>
<td>planHorizon</td>
<td>Planning horizon of the agent</td>
</tr>
<tr>
<td>returnOnInvTHold</td>
<td>Threshold for expected return in investments</td>
</tr>
</tbody>
</table>

The basic set of methods of the *Provider* class is as follows;

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>assessGenPortfolio</td>
<td>Evaluates the profitability of the generators in the portfolio of the provider.</td>
</tr>
<tr>
<td>calculateROIExpected</td>
<td>Returns the expected return on investment (ROI) for an investment option being considered based on market expectations for planHorizon years ahead, and what is known about the option</td>
</tr>
<tr>
<td>makeInvestmentDecision</td>
<td>Returns the investment option that is estimated to provide maximum profit upon completion</td>
</tr>
<tr>
<td>updateMarketInfo</td>
<td>Updates what is known to the agent regarding the market situation (e.g. self-generation popularity, etc.)</td>
</tr>
<tr>
<td>updateOptInfo</td>
<td>Updates the information known to the agent regarding the feasible/considered energy supply options</td>
</tr>
</tbody>
</table>

There are seven instances of *Provider* class in ElectTrans, which correspond to major utilities in the Dutch context.

**f. Market class**

The *Market* object represents the environment where demand and supply-side information meet and aggregated. Most importantly, the end-users agents’ loads that are directed to the grid are aggregated in the *Market*, and the load-duration curve is constructed. Besides, aggregate statistics like total green supply, or consumption are attributes of the *Market* object.

The list of individual variables and methods of the Market object is not very relevant for explaining ElectTrans. Rather, we find the list of issues traced in the Market class regarding the electricity market more informative. The set of issues traced in the *Market* class include the following:

- Active generation capacity by control type (central vs. distributed)
- Active generation capacity by fuel type
- Carbon emissions by source (Central grid, distributed generators)
- Total demand by type (Green vs. gray)
- Generation by source (Central grid, distributed generators)
- Generation by fuel type

Some of the key methods of the *Market* class that are not just related to statistics collections are as follows;
Every instance of ElectTrans has a single instance of the Market class.

**g. OptPract class**

The class represents the options for the practitioner agents. Mainly these options are grouped under two categories; grid-based and distributed ones. The instances of the OptPract class correspond to the state-of-the-art in a particular electricity supply option. For example, small-scale wind turbine is a distributed generation option, and is represented as an instance of this class. The instances of OptPract are characterized mainly by their technological (e.g. fuel efficiency, seasonal availability, emission levels) and economical (e.g. investment and operating costs) properties.

The basic set of variables of the OptPract class is as follows:

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuelType</td>
<td>The energy source used by the option</td>
</tr>
<tr>
<td>efficiency</td>
<td>Average electrical efficiency of the option</td>
</tr>
<tr>
<td>efficiencyMax</td>
<td>Maximum electrical efficiency that is likely to be realized by future developments</td>
</tr>
<tr>
<td>investmentCost</td>
<td>Investment cost per MW capacity</td>
</tr>
<tr>
<td>investmentCostMin</td>
<td>Minimum investment cost per MW capacity that is likely to be realized by future developments</td>
</tr>
<tr>
<td>variableCost</td>
<td>Variable cost of generation per MWh</td>
</tr>
<tr>
<td>variableCostMin</td>
<td>Minimum Variable cost of generation per MWh that is likely to be realized by future developments</td>
</tr>
<tr>
<td>emissionLevel</td>
<td>Carbon emissions per MWh electricity generated</td>
</tr>
<tr>
<td>lifeTime</td>
<td>Average lifetime of the option once installed</td>
</tr>
<tr>
<td>leadTime</td>
<td>Average lead time for installing the option</td>
</tr>
<tr>
<td>ifGreen</td>
<td>Binary variable about whether the option is considered as a green source, or not.</td>
</tr>
<tr>
<td>ifCHP</td>
<td>Binary variable about whether the option is a combined heat-power generator, or not,</td>
</tr>
<tr>
<td>coFireFrac</td>
<td>The fraction up to which biomass co-firing can be done using the option</td>
</tr>
<tr>
<td>techDevFrac</td>
<td>Pace indicator for expected technological developments for the option</td>
</tr>
</tbody>
</table>

The basic set of methods of the OptPract class is as follows:

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>updateAttributes</td>
<td>Updates the technological and economical attributes of the option</td>
</tr>
</tbody>
</table>
There are 16 instances of \textit{OptPract} class in ElectTrans, which can be seen in the sample parameter files given below.

\textbf{h. OptProv class}

The class represents the electricity generation options for the electricity generation companies who feed the central grid. In other words, the instances of \textit{OptProv} are the investment options for the provider agents. The instances of the class correspond to the state-of-the-art in a particular type of electricity generation facility. The instances of \textit{OptProv} are characterized mainly by their technological (e.g. fuel efficiency, minimum load factor, emission levels) and economical (e.g. investment and operating costs) properties.

The basic set of variables of the \textit{OptProv} class is as follows;

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuelType</td>
<td>The energy source used by the option</td>
</tr>
<tr>
<td>efficiency</td>
<td>Average electrical efficiency of the option</td>
</tr>
<tr>
<td>efficiencyMax</td>
<td>Maximum electrical efficiency that is likely to be realized by future developments</td>
</tr>
<tr>
<td>investmentCost</td>
<td>Investment cost per MW capacity</td>
</tr>
<tr>
<td>investmentCostMin</td>
<td>Minimum investment cost per MW capacity that is likely to be realized by future developments</td>
</tr>
<tr>
<td>variableCost</td>
<td>Variable cost of generation per MWh</td>
</tr>
<tr>
<td>variableCostMin</td>
<td>Minimum Variable cost of generation per MWh that is likely to be realized by future developments</td>
</tr>
<tr>
<td>emissionLevel</td>
<td>Carbon emissions per MWh electricity generated</td>
</tr>
<tr>
<td>lifeTimeLB</td>
<td>Minimum expected lifetime of the option once installed</td>
</tr>
<tr>
<td>lifeTimeUB</td>
<td>Maximum expected lifetime of the option once installed</td>
</tr>
<tr>
<td>permsDelay</td>
<td>Average construction time of the option</td>
</tr>
<tr>
<td>constDelay</td>
<td>Average construction time of the option</td>
</tr>
<tr>
<td>availability</td>
<td>Percentage of the yearly cycle a generator is available for generation</td>
</tr>
<tr>
<td>ifGreen</td>
<td>Binary variable about whether the option is considered as a green source, or not.</td>
</tr>
<tr>
<td>ifCHP</td>
<td>Binary variable about whether the option is a combined heat-power generator, or not.</td>
</tr>
<tr>
<td>coFireFrac</td>
<td>The fraction up to which biomass co-firing can be done using the option</td>
</tr>
<tr>
<td>techDevFrac</td>
<td>Pace indicator for expected technological developments for the option</td>
</tr>
</tbody>
</table>

The basic set of methods of the \textit{OptProv} class is as follows;

<table>
<thead>
<tr>
<th>Method name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>updateAttributes</td>
<td>Updates the technological and economical attributes of the option</td>
</tr>
</tbody>
</table>

There are 26 instances of \textit{OptProv} class in ElectTrans, which can be seen in the sample parameter files given below.

\textbf{i. Generator class}

The \textit{Generator} class represents physical electricity generation facilities connected to the central grid. Each instance of this class corresponds to an actual power generator in the Dutch system. In that respect, 76 instances of this class are initialized in the base version of ElectTrans, which represent 76 generators with a capacity more than 15 MW.
Although *Generator* is closely related to the *OptProv* class, the difference should be clear with the following example. A 400-MW combined cycle unit is an investment option for the providers (i.e. an instance of *OptProv*). The conversion efficiency of this option is improving every year. Once a provider decides to invest in one of these, then a physical generation plant is constructed (i.e. an instance of *Generator*). The efficiency of the plant is static and determined by the state of the technology (*OptProv*) at the time of investment. In short, *OptProv* represents technology, whereas *Generator* represents physical installations of this technology at some point in time.

The basic set of variables of the *Generator* class is as follows;

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuelType</td>
<td>The energy source used by the option</td>
</tr>
<tr>
<td>efficiency</td>
<td>Average electrical efficiency of the option</td>
</tr>
<tr>
<td>variableCost</td>
<td>Variable cost of generation per MWh</td>
</tr>
<tr>
<td>emissionLevel</td>
<td>Carbon emissions per MWh electricity generated</td>
</tr>
<tr>
<td>lifeTime</td>
<td>Expected lifetime of the option once installed</td>
</tr>
<tr>
<td>availability</td>
<td>Percentage of the yearly cycle a generator is available for generation</td>
</tr>
<tr>
<td>ifGreen</td>
<td>Binary variable about whether the option is considered as a green source, or not.</td>
</tr>
<tr>
<td>ifCHP</td>
<td>Binary variable about whether the option is a combined heat-power generator, or not.</td>
</tr>
<tr>
<td>coFireFrac</td>
<td>The fraction up to which biomass co-firing can be done using the option</td>
</tr>
<tr>
<td>comStep</td>
<td>Time step when the generator was/will be commissioned</td>
</tr>
<tr>
<td>decomStep</td>
<td>Time step when the generator was/will be decommissioned</td>
</tr>
<tr>
<td>status</td>
<td>Status of the generator (i.e. retired, active, mothballed, announced, under construction,)</td>
</tr>
<tr>
<td>profitHist[year]</td>
<td>Profit of the generator in the year year</td>
</tr>
<tr>
<td>generationHist[year][per]</td>
<td>Electricity generated in the period per of the year year</td>
</tr>
</tbody>
</table>

The instances of the *Generator* class are passive objects mainly controlled by the provider agents. Therefore, they do not have methods relevant to understanding the working of *ElectTrans*. All the methods of this class are more related to book-keeping (e.g. updating generation history), or inter-object communication (e.g. report active generation capacity).

**j. GenCapaPract class**

The class represents the distributed generation capacity of a certain kind owned by a practitioner agent. The correspondence between the *Generator* and *OptProv* classes is identical to the correspondence between the *GenCapaPract* and *OptPract* classes. The major difference of *GenCapaPract* from *Generator* is that it does not represent a discrete generation unit, but an aggregated generation capacity of the same kind. Every time a practitioner installs new wind turbines, the aggregate wind turbine capacity controlled by the practitioner (an instance of the *GenCapaPract* class) is increased, rather than creating new instances of the *GenCapaPract* class.

The basic set of variables of the *GenCapaPract* class is as follows;
The instances of the GenCapaPract class are passive objects mainly controlled by the practitioner agents. Therefore, they do not have methods relevant to understanding the working of ElectTrans. All the methods of this class are more related to book-keeping (e.g. updating capacity), or inter-object communication (e.g. report depreciated capacity).

**k. OptionInfoPract class**
This class is the first of three, so called, information classes in ElectTrans. This class represents the information a practitioner agent has about an instance of OptPract. For example, wind turbine is a practitioner option. A practitioner agent’s information about the technical and economical properties of this option is registered in an instance of the OptionInfoPract class, which corresponds to wind turbine option. In a sense, the instances of this class can be considered as individual files an agent keeps about existing technological options.

Important variables of this class are almost identical to the ones of OptPract class.

Since every agent keeps track of available technological options, there are 16 instances of this class for each agent. Considering that the base version of the model includes 400 agents, there are maximum 6400 instances of this class in ElectTrans.

**l. OptionInfoProv class**
This information class is related to what provider agents know about central generation options. Similar to the case of OptInfoPract, the instances of this class can be considered as files a provider agent keeps about possible capacity investment options.

**m. GeneratorInfo class**
This information class is related to what provider agents know about existing and planned generation facilities in the system. The instances of this class can be considered as files a provider agent keeps about generation plants. These information files are used in the feasibility analyses conducted by the providers.

---

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Short description</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>coFireFrac</td>
<td>The fraction up to which biomass co-firing can be done using the option</td>
</tr>
<tr>
<td>capacity</td>
<td>Operational generation capacity</td>
</tr>
<tr>
<td>capaPlanned</td>
<td>Planned generation capacity (i.e. under construction)</td>
</tr>
</tbody>
</table>

3 This is the maximum number. Since not all options are appropriate for all practitioner agents, some of the agents may keep record of less than 16 options.
The presence of very closely related classes (e.g. OptProv, Generator, OptInfoProv, and GenInfo; or OptPract, GenCapaPract, and OptInfoPract) may make the structure of ElectTrans difficult to comprehend. A very simple demonstrative example may help to clarify the relationship of these related classes. Figure C.1 demonstrates an example for the provider-related classes. Agent A owns a generator, Facility F, which is an instance of Generator. Agent B has some information about Facility F, which need not be precise about the issues like effective capacity, operating costs, or decommissioning date. This information is kept in an information file owned by the Agent B, and this information file is an instance of GeneratorInfo. Both agents are aware of the existing options, but what they know about the technical properties of the options need not be neither identical, nor perfect. In other words, both agents keep their own files about the existing options using their private instances of OptInfoProv. A very similar situation is valid for the practitioner-side classes; i.e. OptPract, GenCapaPract, and OptInfoPract.

Figure C.1. An example on the relationship of provider-related classes

C.3. Pseudocode of ElectTrans
As will be apparent in the pseudocode, ElectTrans incorporates two different action cycles. The fast cycle takes place for every time step, which is a quarter-year in the base version of the model, and this cycle is more related to the operational developments related to the agents. The slow cycle is more about slower decisions such as capacity investments, and alike. The slow cycle is activated at the end of each year in ElectTrans.

Initialize the model instance |
Link to the parameter file
Link to the scenario file
Create the market environment
Create the options for the provider agents
Create the provider agents
Initialize the existing generation facilities, i.e. the \textit{generators}.

Create the \textit{options} for the \textit{practitioner} agents.

Create the \textit{practitioner} agents.

\}

Repeat until the time step is equal to the simulation final time \{

Repeat until all \textit{practitioners} are considered \{

Randomly pick one \textit{practitioner} agent.

Ask the agent for its demand allocation \textit{(allocateDemand)}.

\}

Aggregate the demand in the \textit{market} \textit{(collectDemandData)}.

Dispatch load in the market to the active generators on the grid \textit{(dispatchLoad)}.

Update market statistics related to generation, emissions, and prices.

Repeat until all \textit{generators} are considered \{

Pick a \textit{generator}.

Update its registry regarding generation, revenue, and costs.

\}

If the time-step corresponds to the last period of a year \{

Update green certificate prices in the \textit{market} \textit{(setGreenCertPrice)}.

Update fuel prices in the \textit{market} \textit{(updateFuelPrices)}.

Update yearly statistics in the \textit{market}.

Repeat until all \textit{providers} are considered \{

Randomly pick one \textit{provider} agent.

Update agent’s information about the \textit{options} \textit{(updateOptInfo)}.

Update agent’s information on the market conditions \textit{(updateMarketInfo)}.

Ask the agent to assess the \textit{generators} in its generator park \textit{(assessGenPortfolio)}.

Ask the agent for its investment decision \textit{(makeInvestmentDecision)}.

If the agent decides for capacity investment \{

Create a new \textit{generator}.

\}

\}

Repeat until all \textit{practitioners} are considered \{

Randomly pick one \textit{practitioner} agent.

Update agent’s information about the \textit{options} \textit{(updateOptInfo)}.

Ask the agent to plan for its free-demand \textit{(planCapaForFreeDemand)}.

Update the distributed generation capacity controlled by the agent \textit{(updateGenCapa)}.

Update agent’s demand for electrical power \textit{(updateDemand)}.

\}

Repeat until all \textit{provider options} are considered \{

Pick an \textit{option}.

Update the properties of the \textit{option} \textit{(updateAttributes)}.

\}

Repeat until all \textit{practitioner options} are considered \{

Pick an \textit{option}.

Update the properties of the \textit{option} \textit{(updateAttributes)}.

\}

Repeat until all \textit{generators} are considered \{

Pick a \textit{generator}.

Update the status of the \textit{generator} \textit{(updateStatus)}.

\}

\}

End simulation.
C.4. Description of the agent actions

a. Practitioner actions

i. allocateDemand

The amount of electricity supplied from each available source is calculated in this method. Available sources for an agent are grid electricity and distributed generation capacity owned by the agent, if it owns some. The fundamental assumption in the source selection for an agent is that an agent uses distributed generation sources as much as possible before using the grid as a source. For example, assume the energy demand of the agent is 300 kWh in a certain period, and the agent owns wind turbines that can deliver 100 kWh during this demand period. Then the agent uses 100 kWh from turbines, and the rest of the demand is supplied from the central grid.

The method works as follows;

Repeat for each type of generation capacity that is owned by the agent{
  Calculate the maximum energy that can be supplied during the current period
  (considering the seasonality of some distributed generation options, such as wind-based, or solar-based ones)
}
Aggregate the total supply from the actor's distributed generators
Register the remaining demand of the agent to be supplied via central grid

ii. updateOptInfo

The agent updates the information it keeps in the option files (OptInfoPract) regarding the options (OptPract). The practitioner updates information related to the following properties of distributed generation options; efficiency, investment cost, fixed operating cost, variable operating cost, emission levels, and diffusion level among peers. A first-order information delay formulation is used to represent the way agents' perceptions are updated;

\[
Info_{\text{perceived}}(\text{step}) = Info_{\text{perceived}}(\text{step} - 1) + Info_{\text{Correction}}(\text{step}) \quad \text{[C.1]}
\]

\[
Info_{\text{Correction}}(\text{step}) = \frac{Info_{\text{actual}}(\text{step} - 1) - Info_{\text{perceived}}(\text{step} - 1)}{\text{learningDelay}} \quad \text{[C.2]}
\]

iii. planCapaForFreeDemand

The concept of 'free-demand' is of primary importance in order to understand the functioning of the method. A practitioner agent represent a group of end-users, and this agent owns supply contracts (for grid-based supply) and generation capacity (for supply from distributed generation). At the end of each year, some contracts expire and generation capacity retires. The first component of the free-demand is the demand that was previously supplied from these lost sources. Additionally, the demand of the agent might have increased. In this case, there is some new demand, and this additional demand is the second component of the free-demand for the agent. This method is related to the agent making a capacity plan related to the

4 'Peers' of a practitioner agent are the other agents of the same practitioner-type.
sources to be used to satisfy this free-demand in the following time steps. This means making new supply contracts, and/or making new distributed generation capacity installments.

The method works as follows;

Calculate the free-demand of the agent
Calculate expected utility for available options as power sources (calculateOptUtils)
For each practitioner option do the following
   Calculate the share in supplying the free-demand
   Calculate the additional capacity required to satisfy this new demand
   Register the required capacity as planned supply

The expected utilities for the options are calculated as follows (calculateOptUtils);

First the properties (i.e. attributes) of the option are normalized. In normalization, the properties of the gray grid electricity are used as the reference levels. The normalization is conducted as follows;

\[
\hat{a}_{opt, prop} = \frac{a_{opt, prop} - \hat{a}_{prop}}{\hat{a}_{prop}}
\]  

where \( \hat{a}_{prop} \) is the reference level for the property \( prop \), and \( a_{opt, prop} \) is the level of option \( opt \)’s property \( prop \) according to what is known to the agent. In other words, \( a_{opt, prop} \) values come from \( OptInfoPract \) objects.

Using the normalized properties, the agent calculates a utility for the option;

\[
util_{opt} = \prod e^{\alpha_{prop} \hat{a}_{opt, prop}}
\]  

where \( \alpha_{prop} \) is the priority of the property \( prop \) for the agent.

The share of an option is supplying the free-demand is calculated as follows;

\[
share_{opt} = \frac{util_{opt}}{\sum_{i \in Options} util_{i}}
\]

Capacity required for an option to supply the new energy demand is calculated as follows;

\[
capacityExtra_{opt} = \frac{freeDemand \times share_{opt}}{availability_{opt} \times 8760}
\]

---

5 To be more precise, it is the priority of the issue that is directly related to that property of the option. For example the issue can be cost minimization, and the property can be cost of generation.
where availability stands for the yearly average availability of the option. In other words, which fraction of the 8760 hours in a year the option can be used to generate electricity.

**iv. updateGenCapa**

The method updates the state of distributed generation sources the agent controls. This includes updating the effective capacities of the already possessed ones, and also introducing new distributed generation source if the agent decided to adopt some in the recent decision round.

One important aspect of the method is about property updating. Since the generation capacity represents an aggregated capacity rather than distinct generation facilities, its properties of the generation capacity is actually the average of the properties aggregated into this variable. For example, if the agent adopted a 10 kW wind turbine capacity with operating cost of X, and then another 10 kW with an operating cost of Y, the agent possesses a generation capacity of 20 kW with an operating cost of \((X+Y)/2\). Therefore, at every time step the properties of this aggregate generation capacity should be updated based on the amount of new capacity installed and the amount of existing old capacity.

For each of the feasible distributed generation options, the agent performs the following:

- Calculate the capacity depreciated/retired

\[
\text{capaDepr} = \frac{\text{capaTotal}}{\text{lifeTime}}
\]  

[C.7]

- Calculate the capacity from the old time-step that remains operational

\[
\text{capaTotalOld} = \text{capaTotal} - \text{capaDepr}
\]  

[C.8]

- Calculate the new capacity that will be installed and become effective in the current time step. This depends on the capacity already planned by the agent in the past, and the installation lead time of the corresponding generation option;

\[
\text{capaNew} = \frac{\text{capaPlanned}}{\text{leadTime}}
\]  

[C.9]

- Update the properties of the generation capacity using a weighted average;

\[
\text{prop} = \frac{\text{propOld} \times \text{capaTotalOld} + \text{propNew} \times \text{capaNew}}{\text{capaTotalOld} + \text{capaNew}}
\]  

[C.10]

where \(\text{capaNew}\) is the capacity recently installed.

- Update the total generation capacity;

\[
\text{capaTotal} = \text{capaTotalOld} + \text{capaNew}
\]  

[C.11]
v. updateDemand

Reading the scenario file, the method gets the average demand growth percentages for the agent. Using this percentage, the method updates the power demand of the agent for each period of the following simulation year;

\[
demandGrowthFrac_{\text{period}} \sim \mathcal{N}(\mu, \sigma) \tag{C.12}
\]

\[
\mu = demandGrowthAvg, \quad \sigma = 0.1 \times demandGrowthAvg
\]

\[
demandGrowth_{\text{period}} = demand_{\text{year}, \text{period}} \times demandGrowthFrac_{\text{period}} \tag{C.13}
\]

\[
demand_{(\text{year}+1), \text{period}} = demand_{\text{year}, \text{period}} + demandGrowth_{\text{period}} \tag{C.14}
\]

The demand growth percentage for each period of the year is determined using a Gaussian distribution with mean \( demandGrowthAvg \), and a standard deviation equal to the 10% of this average.

b. Provider actions

i. updateOptInfo

The agent updates the information it keeps in the option files (OptInfoProv) regarding the options (OptProv). The practitioner updates information related to the following properties of distributed generation options; efficiency, investment cost, fixed operating cost, variable operating cost, emission levels, and yearly operational availability. A first-order information delay formulation is used to represent the way agents’ perceptions are updated. The formulation is identical to the one given in Equations C.1 and C.2.

Besides updating the agent’s information regarding already known options, the method also updates the list of options considered by the agent for investment. For example, a new option may be investable at an intermediate stage of the simulation, such as the options with carbon capture and storage. The method checks the scenario file, and reads the activation year\(^6\) for all the provider options. If there is a new option becoming commercially available at that stage of the simulation, the agent creates a new information file (OptInfoProv) for this new option, and adds it to the list of considered investment possibilities.

ii. assessGenPortfolio

The agent performs assessment regarding three main issues in this method. The first one is about the fuel mix of the conventional combustion-based generators. The second one is regarding mothballing/reactivation of the existing generators. The last of the three decisions is related to re-evaluation of investment projects planned in the past.

Biomass co-firing has the potential of becoming profitable as function of biomass costs, and the benefits due to carbon emissions avoided by replacing gas or coal with biomass. Following indicator is used to evaluate the ration of benefits (emissions costs avoided by using biomass to generate 1 unit of electrical energy) to costs (extra fuel cost due to using biomass instead of coal to generate 1 unit of electrical energy);

\(^6\) The simulation year beyond which a generation technology becomes commercially available. This parameter is specified as a part of the scenario specification.
If the ratio is above 1, the agent shifts the generator to the co-firing mode. If the ration is below 1, and the generator is already in the co-firing mode, the agent shifts the generator back to 100% coal-firing mode.

Mothballing is an action that an agent can take in case of having generators making losses. The agent checks the profit history of the active generators it owns, and in the case of loss-making one, the agent temporarily deactivates it. Being different from a decommissioned generator, a mothballed generator can be reactivated if the market conditions change. Mothballing can also be used for strategic reasons in order to prevent other agents from making capacity investments.

A decision directly related to mothballing is the reactivation of mothballed generators. For this decision, the agent calculates the expected profit to be made if the generator is activated for the following year. In order to calculate this, the agent runs a simulation of the market (i.e. a sub-simulation, within the main simulation). The agent uses its information about the market (i.e. fuel prices, power demand, other generators connected to the grid, etc) to construct an expected market setup for the following year. In order to do so, the agent first constructs a list of generators that are expected to be active next year. This list involves the currently active generators, since the agent assumes that they will continue to be active. The agent adds new generators to this list, if there are generators that are under-construction to be completed by next year. Then the agent forecasts the expected load and fuel prices. The forecasting is done based on the records that the agent keeps about the historical load and prices, and works as follows (identical for both fuel prices, and load);

\[
\text{loadAvgChg} = \frac{\text{loadRecent} - \text{loadAvg}}{\text{trendHorizon}} \tag{C.16}
\]

where \(\text{loadAvg}\) is the historical average of the load experienced in the previous years.

\[
\text{loadTrend} = \frac{\text{loadAvgChg}}{\text{loadAvg}} \tag{C.17}
\]

\[
\text{loadAvg}(\text{step}) = \text{loadAvg}(\text{step} - 1) + \text{loadAvgChg} \tag{C.18}
\]

\[
\text{loadForecast} = (1 + \text{loadTrend})^{\text{forecastHorizon}} \text{loadAvg} \tag{C.19}
\]

Using the forecasted figures, and the generators that are expected to be active, the agent calculates how much load will be dispatched (dispatching algorithm will be discussed below) to the particular generator being considered, and how much profit can be expected. If there is some profit opportunity, the mothballed generator is activated. In other words, the generation unit is committed for the next year. Otherwise, the generator is left as mothballed until the end of the following year.
In some experiments, a generator making loss during the last 3 years is mothballed. However, it was not possible to reach reliable information about the criteria used by the generation companies in their mothballing decisions. Therefore, in the experiments reported in Chapter 10, the agents are not allowed to mothball their generators.

A generator with the status of ‘announced’ actually represents an investment project whose constructions did not start yet. The agents also assess their projects before they proceed into the ‘under-construction’ stage in order to check whether they are still profitable. As in the case of activation of mothballed generators, the agent runs a simulation about the market conditions for a future time point. If an announced project is not profitable anymore, the agent can cancel it.

### iii. makeInvestmentDecision

This method calculates the expected return on investment (ROI) for the available investment options, and returns the most profitable one as a result. If the maximum ROI that can be obtained by available investment options is still below the ROI threshold of the agent, the method returns a ‘no investment’ decision. In brief the method works as follows;

```
Repeat until all investment options are considered {
    Pick an investment option
    Calculate expected ROI for the option
    If the ROI is greater than the maximum ROI calculated so far {
        Update the maximum ROI
    }
}

If the maximum ROI is higher than the ROI threshold {
    Return the investment option that yields maximum ROI as the investment decision
}
Else the investment decision of the agent is not to make any investment
```

The most important part of the investment decision is the calculation of an expected return on investment. Briefly, the expected ROI is calculated based on annual cost and revenue terms expected \( planHorizon \) years in the future. The cost terms include investment costs, as well as operating costs. The revenue terms include direct income from the sales of generated electricity, as well as other payments such as subsidies.

The investment cost is converted into annual cost terms spanning the lifetime of the facility. In other words, the total investment cost is converted into levelized annual terms.

\[
invCostAnnual = \frac{invCostTotal \times r \times (1 + r)^{\text{lifeTime}}}{(1 + r)^{\text{lifeTime}} - 1}
\]  \[C.20\]

where \( r \) is the interest rate in the market.

Another cost term is the fixed operating cost of the generation unit, which is dependent mainly on the capacity of the unit, and independent of the generated electricity.

\[
fixedCostAnnual = fixedCost_{\text{option}} \times capacity_{\text{option}}
\]  \[C.21\]
The third cost term is about the variable costs of the generation unit, which is dependent on the amount of electricity the unit will generate in a year. In order to calculate the variable costs, the agent makes a forecast about the expected generation amount when the unit becomes operational.

The forecasting algorithm of the agent works as follows;

Forecast the fuel prices
Forecast the generation-based extras
Forecast the load on the central grid
Repeat until all information files on generators are considered {
   Pick a generator
   If the generator is active {
      Check the expected decommissioning date
      If the generator is expected to be active in the forecasted year, add it to the future generator list (futureGenList)
   }
   If the generator is under-construction {
      Add the generator to the future generator list (futureGenList)
   }
}
Add the currently considered generation unit to the futureGenList
Conduct an experimental load dispatching, and calculate the load dispatched to the generation unit being considered for investment.

According to this forecasting procedure, the agent first constructs a sort of mental image of what it expects the market conditions to be by the time the considered new investment will be operational. Then, simulates this mental image to check how competitive this new investment can be by then, and the expected amount of load it can attract to this new facility to be constructed. Based on this expected generation (i.e. genExp), the agent calculates other cost and revenue terms;

\[
\text{genCostAnnual} = (\text{fuelCost} + \text{variableCost})\text{genExp} \quad \text{[C.22]}
\]

\[
\text{fuelCost} = \frac{\text{fuelPrice}}{\text{efficiency}_{\text{opt}}} \quad \text{[C.23]}
\]

The experimental load dispatching conducted by the agent also provides expected revenue from electricity generation (i.e. genRevExp). Combining these cost and revenue terms, the agent calculates the yearly profit level;

\[
\text{profitAnnualExp} = \text{genRevExp} - \text{totalCostAnnual} \quad \text{[C.24]}
\]

where;

\[
\text{totalCostAnnual} = \text{genCostAnnual} + \text{fixedCostAnnual} + \text{InvCostAnnual}
\]

\[
\text{roiExp} = \frac{\text{profitAnnualExp}}{\text{InvCostAnnual}} \quad \text{[C.25]}
\]
The calculations given in Equations C.20 through C.25 are purely financial, and do not consider the technical feasibility. Depending on the technology that is related to the considered option (e.g. coal incineration in the case of a 500MW conventional coal-based generator), there are some technical considerations such as the expected minimum up time. Independent of the expected profit levels, a base-load generator cannot be implemented if the expected up time of the generator is, for instance, 10%. This is mainly due to the long start-up and stepping-up times required in a generation unit. As a result, using the genExp figure, expected up time of the generation unit is also calculated. If this figure is less than the minimum up time of the generation technology, the investment option is considered as an infeasible one.

c. Market actions

i. collectDemandData

Following the demand allocation of the practitioner agents, the market object collects individual demand figures from the agents for each time period of the year. This way the market object constructs a load-duration curve for each period of the year. In the base version of ElectTrans, every period corresponds to a quarter of the year. This is mainly due to the generation options covered in the model that have some seasonality in their supply patterns (e.g. PV roof, wind turbines, heat-driven cogeneration plants). Due to this seasonality, endogenous developments about the shares of these options in the electricity supply may cause differing dynamics on seasonal demand on the central generation. For example, increase in solar panels on roofs may yield less demand on the central grid in summer (3rd quarter), while not changing much the demand in winter (1st quarter). Hence, load-duration curves of quarters are represented separately in the model.

One way to represent a quarterly LDC is to approximate it with a constant average power demand level. This level can easily be obtained by summing up the individual demand levels of the individual practitioner agents. Such a representation flattens out the actual LDC, has the potential to distort dispatching (e.g. more generation by base-load plants, no load on peak-load plants). Therefore, another approach is used to represent/construct LDCs in ElectTrans; developing LDC templates that resemble the actual LDCs in the Dutch system, and then customize these templates based on the instantaneous average load levels at every step of the simulation. We have constructed quarterly LDCs for 2006, 2007, and 2008 using the load data published by TenneT for 15-min intervals. As can be seen in Figure C.2, the Dutch LDCs do not demonstrate very rapid changes at the edges, and have a very linear character in between. This visual observation is also supported by our regression analyses, in which linear functions have $R^2$ values above 0.99.

Each quarter’s LDC is represented with a linear function in the following form;

$$ f(t) = \text{loadMax} - \eta t \quad \text{[C.26]} $$

where $\eta$ is the slope of the LDC, which is specific to the time period (i.e. quarter)

---

7 To be more precise, it can be implemented to serve 10% of the time, but the fact that the generator needs to be ready to supply all the time makes this an inconvenient action. Keeping a coal-based facility ready to supply electricity implies using fuel on continuous basis without generating any electricity, which would change the figures of the profitability analysis, and result in a negative outcome.
Going back to how the demand collection method functions, the average load in a period is determined by aggregating the average loads of individual agents. Then this average is used to calculate $loadMax$. Quarter-specific slopes are model parameters specified in the parameter file.

$$loadMax = loadAvg + \eta \left( \frac{loadPeriodDuration}{2} \right)$$  \hspace{1cm} \text{[C.27]}$

**ii. dispatchLoad**

We assumed that a load dispatching on merit order takes place in the actual system. According to this, generators connected to the central grid are ordered according to their marginal generation costs. Then starting from the lowest cost option, the load is dispatched to the available generators. Before describing the algorithm implemented in order to conduct such a load dispatching process, a simple example is given below to clarify the process better (see Figure C.3).
The negative-sloped dark line in Figure C.3 represents the LDC for a certain time interval (e.g. year, or quarter year). There are 3 active generators, and they are numbered in the order of increasing marginal generation cost (i.e. Generator 1 has the lowest marginal cost). The dispatching starts with Generator 1. During interval 1, the capacity of Generator 1 is enough to supply all demand. Being the most expensive generator that supplies electricity during interval 1, the marginal generation cost of Generator 1 sets the electricity price in this period; the price for interval 1 equals to \( MC_1 \). Then Generator 2 is called for supply. Both Generator 1 and Generator 2 supply electricity during Interval 2, and Generator 2 sets the price of the interval; the price in interval 2 equals \( MC_2 \). Finally, all three generators supply during interval 3, and the price of this interval equals \( MC_3 \).

The Y-axis of the figure is power, and the X-axis is time. Therefore, the area under the LDC corresponds to energy. In that respect, when we look at the total electricity energy generated by a specific generator, the amount is equal to the sum of the areas of the sections indicated by the name of the generator. For example, for Generator 2, total energy supply is equal to the sum of areas of section B and C.

The revenue of a generator is calculated by using the price of a certain interval and the amount of energy delivered by the generator during that interval. The total revenue of Generator 1 can be calculated as follows:

\[
\text{Total Revenue} = \text{Revenue}_{\text{Int}_1} + \text{Revenue}_{\text{Int}_2} + \text{Revenue}_{\text{Int}_3}
\]

\[
\text{Revenue}_{\text{Int}_1} = MC_1 (I + F), \quad \text{Revenue}_{\text{Int}_2} = MC_2 (H), \quad \text{Revenue}_{\text{Int}_3} = MC_3 (G)
\]  \[\text{C.28}\]

As can be seen from Equations C.28 and C.29, determining the boundaries of the time interval is necessary for the calculations about the total generation of plants and the electricity prices. Using Equation C.26, the boundaries of the intervals in the given example can be determined as follows;

Interval 1:
\[
\text{UpperBoundary} = t_{\text{max}}
\]
\[
\text{LowerBoundary} = \frac{\text{LoadMax} - \text{Capa}_{\text{Gen}1}}{\eta} = t_1
\]  \[\text{C.30}\]

Interval 2:
\[
\text{UpperBoundary} = t_1
\]
\[
\text{LowerBoundary} = \frac{\text{LoadMax} - (\text{Capa}_{\text{Gen}1} + \text{Capa}_{\text{Gen}2})}{\eta} = t_2
\]  \[\text{C.32}\]

Interval 3:
\[
\text{UpperBoundary} = t_2
\]
\[
\text{LowerBoundary} = 0
\]

since \( \text{Capa}_{\text{Gen}1} + \text{Capa}_{\text{Gen}2} + \text{Capa}_{\text{Gen}3} \geq \text{loadMax} \)  \[\text{C.35}\]
The algorithm used to conduct load dispatching according to this depiction is given below:

Repeat until all active generators are considered {
    Get the marginal generation cost (i.e. price bid) of the generator
    Add the generator to the potential generator list (P)
}
Order the set P in increasing marginal generation cost
Initialize interval counter \( i = 1 \)
Initialize the considered generator list as an empty set (\( C = {} \))
Initialize the cumulative capacity variable \( \text{cumCapa} = 0 \)
Initialize the interval upper bound variable \( t_{\text{up}} = t_{\text{max}} \)
Repeat until \( \text{cumCapa} > \text{loadMax} \), or the set \( \tilde{P} \) is empty {
    Get the first generator from \( P \) as the currently considered generator; \( \text{gen} \)
    Get the effective capacity of the \( \text{gen} \); \( \text{capa}_{\text{gen}} \)
    Calculate \( t = (\text{loadMax} - (\text{cumCapa} + \text{capa}_{\text{gen}}))/\text{slope} \)
    If \( (t > t_{\text{up}}) \), do the following {
        Increase \( \text{cumCapa} \) by \( \text{capa}_{\text{gen}} \)
        Remove \( \text{gen} \) from \( P \)
        Add \( \text{gen} \) to \( C \)
    }
    Else, do the following {
        Set the duration of the current interval, \( d = t_{\text{up}} - t \)
        Set the price of the current interval, \( p_i = \text{margCost}_{\text{gen}} \)
        Update \( t_{\text{up}} \); \( t_{\text{up}} = t \)
        Increase \( \text{cumCapa} \) by \( \text{capa}_{\text{gen}} \)
        Increase interval counter \( i \) by 1
    }
}

\[ d. \text{ OptProv actions} \]

\[ i. \text{ updateAttributes} \]
The attributes are mostly technical, and updated according to the following formulation according to which the attribute level converges to the expected best levels in the long run. The term in the parenthesis represents the room-for-development for the property.

\[ e. \text{ OptPract actions} \]

\[ i. \text{ updateAttributes} \]
As already discusses, there are two main classes of practitioner options. The first group contains the grid-based options, and includes conventional gray and green electricity. The properties of these options that are relevant to the practitioners are the cost of electricity and the emissions caused due to grid-based supply. As can be clearly seen, none of these properties is purely technological properties, and they depend on the way whole grid-based system has been functioning. In that respect, these two properties for the grid-based options are calculated as follows;

Repeat until all generators are considered {
    Get the total amount of electricity generated by the generator in the previous period, and update the cumulative generation of the system
Get the total revenue of electricity generated by the generator in the previous period, and update the cumulative cost of the system.
Get the total emissions from the generator in the previous period, and update the cumulative emissions of the system.

Calculate recent average cost (cumulative cost/cumulative generation)
Calculate recent average emissions (cumulative emissions/cumulative generation)

For the distributed generation options, the formulation given above in the Equations C.36 and C.37 are used.

\[
\text{ChangeInProperty} = (\text{Property}_{\text{Best}} - \text{Property}_{\text{Current}}) \cdot \text{techDevFrac}
\]  

\[
\text{Property}_{\text{Current}}(\text{step}) = \text{Property}_{\text{Current}}(\text{step} - 1) + \text{ChangeInProperty}
\]

\[\text{[C.36]}\]
\[\text{[C.37]}\]

**f. Generator actions**

**i. updateStatus**

This method checks the current simulation step, and the planned commissioning and decommissioning steps of a generator. As a result, changes the status of a generator if necessary. Basic checks, and resulting actions in this method are as follows;

- A generator with 'under-construction' status becomes 'active' if the \( \text{comStep} \) is equal to the current \( \text{step} \).
- A generator with 'active status becomes 'retired' if the \( \text{decomStep} \) is equal to the current \( \text{step} \).
- If the generator is mothballed, its \( \text{decom} \) step is pushed 1 step further.
- If a planned generator is cancelled, its \( \text{comStep} \) is set to infinity.

**C.5. Parameter file**

**a. Base parameters**

**i. Generation plants**

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#### Practitioners

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ii. Provider options

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Summary

This study belongs to the cluster of analytical transition studies, and focuses on the dynamics of transitions, specifically in the context of socio-technical systems, and on the means of studying these dynamics. Mainly driven by the insufficiency of qualitative approaches in explaining transition dynamics, our main research objectives are set to be;

- Investigation of simulation-supported analysis in order to identify potential contribution and limitations of the approach in studying transition dynamics.
- Development of a general conceptual framework, which is compatible with simulation-supported analysis, for analyzing transition dynamics in socio-technical systems.

The first part of the research is a methodological investigation and discussion, which focuses on simulation-supported analysis by taking into account different approaches, techniques and applications. The second part of the research is about the actor-option framework, which is developed as a general basis for simulation-supported analyses of transition dynamics. In the third part of the research, we explore the usability of the actor-option framework in simulation-supported analyses through conducting three modelling studies.

Part I: Simulation-supported analysis in transition studies

It is the transition path taken and the way this path is shaped that is of interest in analytical transition studies, more than the final state of the studied system, or any other static concept. However, the systems that are studied in the transition field are typically complex adaptive systems, and they demonstrate dynamic complexity, which is almost impossible to analyze through qualitative approaches. This study advocates computational approaches in general, and computer simulation in specific, as promising ones for analyzing the complexity of transition dynamics. While we provide a comprehensive methodological discussion in Part I, we mainly focus on three issues; the different ways in which simulation models can be used in transition studies, the major limitations of using simulation models in analyzing transition dynamics, and different approaches through which such models can be developed.
a. Model-use in transition studies

As a consequence of simulation-supported analyses’ ongoing evolution following its introduction to social sciences, it is possible to identify different uses of models in studying social phenomena. Three of these uses, which are highly relevant for transition studies, are discussed in Chapter 2. Briefly, these three model-uses are as follows;

- **Case-specific insight development:** Exploration of plausible transition trajectories for a particular socio-technical system
- **Generic insight development:** Studying behavioural consequences of a set of interacting processes under various circumstances using generic models
- **Theory development and refinement:** Evaluation and refinement of a proposed theory that claims to explain transition dynamics using models that are developed based on the premises of the theory

We also discuss that simulation-supported analysis is traditionally associated only with the first type of model-use, such an association undermines the potential of the approach by overlooking the other two uses.

b. Modelling approaches for transition studies

In Chapter 3, we review a set of established modelling paradigms used for analyzing socio-economical phenomena, i.e. econometrics, micro-simulation, system dynamics (SD), and agent-based (AB) modelling. Considering the dominant perspectives, and the overall objectives in transition studies, we recognize the latter two approaches, as promising ones for transition studies, and further investigate them, especially with regard to the conceptual frames they impose.

We discuss that it would be misleading to assume a single approach as the *magic bullet*, considering the multi-dimensional nature of the transition problem, and the variety of potential uses of models within this context. Similarly, it is hard to speak about a single comprehensive model to study all aspects of transitions. We conclude that it is misleading to make a general statement about which approach works better in transition studies, since SD, AB, and hybrid models (i.e. models that combine SD and ABM components) have different merits that fit to different challenges within transition studies field.

c. Challenges for simulation-supported analyses of transition dynamics

In Chapter 2, we discuss a set of shortcomings, and related methodological challenges for simulation-supported analysis when it is considered in the context of analyzing transitional change. The main shortcomings and related challenges regarding the approach stem from three major issues; *modelling the social, capturing the novelty*, and *role of contingencies*. Major implications of these issues for simulation-supported analyses, in general, and for the three modelling uses discussed in Chapter 2, in specific, are discussed in Section 2.4 in detail.

Part II: The actor-option framework

Part II introduces the *actor-option* framework for modelling socio-technical systems. Detailed case studies of various transitions, and transition-related change processes constituted the empirical basis for the *actor-option framework*, which briefly provides a set of basic building blocks and a set of change *mechanisms* related to these for developing explanatory models.
a. Basic building blocks of the actor-option framework

Transitional change dynamics in socio-technical systems are a result of conjoint changes in social and techno-physical aspects of the system. These aspects have their own internal dynamics, and they differ significantly in their nature. As a result, we concluded that in order to explain transition dynamics properly, dynamics on social and techno-physical aspects should be considered simultaneously, but separately. One of the building blocks of the framework (i.e. actor) is considered for representing the social elements of the system. The state of the techno-physical world is very important in shaping the behaviour of the actors’ in the context of a societal function. Especially, the techno-physical elements that constitute alternatives for the actors regarding the fulfilment of the societal function are of primary importance in this sense. The second building block of the framework, i.e. option, corresponds to such alternatives.

The actor heterogeneity plays an important role in shaping transition. We suggest, firstly, explicit representation of the key aspects that may differentiate actors in terms of their behaviour, and especially choices, within a transition context; preferences, references, commitments. Secondly, we propose categorizing actors into four different role types, which differ in the impact on the system of the choices made by an actor. These four actor roles, i.e. regulators, providers, practitioners, opinion groups, are discussed in detail in Chapter 4. An option in the actor-option framework is a broader concept than a stand-alone technology or an artefact, and it is characterized by, so called, embodied and disembodied properties. Embodied properties are related to the techno-physical nature of an option, and they can be observed even when the option is isolated from its socio-economical context. Disembodied properties are related to the context in which the option functions.

b. Mechanisms of change

The general conceptual representation aimed with the actor-option framework is primarily to explain transitional change in terms of endogenous processes of change; i.e. mechanisms. These mechanisms are primarily related to changes of options in relation to actors’ choices, changes of actors’ information about their environment and available options, and changes in the identity of the actors that condition their choices. In our analyses, we identified 10 general mechanisms under three different groups (i.e. mechanisms on option change, on actors’ knowledge, on actors’ identity), and these mechanisms are discussed in detail in Chapter 5.

Our inductive analysis of case studies from the literature resulted in a conceptual framework, which identifies building blocks, and a set of mechanisms. These mechanisms explain how these blocks interact and change, and consequently shape system’s transition dynamics. In that respect, the actor-option framework is not a general transition model, but it is a compilation of modular concepts (i.e. actors, options, and mechanisms) for developing models that are case-specific, or generic at some level.

Part III: The actor-option framework in use

In the third part of the study, we apply the actor-option framework in three modelling studies. Additionally, we also discuss the extent to which the framework can serve as a general conceptual basis, and its conceptual and practical limitations. Furthermore, the analyses conducted with the models provide evidence regarding the basic premises of the framework.
Two of the studied cases are historical transitions; transition in the Dutch waste management system, and transition in the British naval transportation system. The third case focuses on the current state of the Dutch electricity system, and its plausible change dynamics. As we discuss in Section 11.2, the framework can successfully be applied to these different contexts without difficulty. This provides us important evidence about the contextual generality of the framework. Besides, we also show that the framework can be used to support analyses at differing aggregation levels by developing models that differ in aggregation. Among these the WasteTrans model is the most aggregate example, whereas the ElectTrans model has the least aggregation in terms of both the options and the actors. In these three studies, we demonstrate that the models developed using the framework can be used to explore social (e.g. norms, preferences), regulatory (e.g. market regulations, subsidy schemes), and techno-physical aspects (e.g. new technologies). As we discuss in Section 11.4, the models presented in Chapters 8 through 10 constitute examples for the different models-uses discussed in Chapter 2. This way we further clarify the differences between these three uses and their potential contributions by examples.

The actor-option framework builds on three fundamental premises briefly about the importance of explicitly addressing the social actors, avoiding the aggregation of system elements of different natures, and staying at a policy-relevant abstraction level. During the analyses with the three models, we identify a set of circumstances that support the importance of these premises in explaining the observed transition dynamics. These circumstances, on which we reflect in Chapter 11, support the design choices made in developing the actor-option framework.

The three modelling applications of the framework provided us the opportunity to investigate the limitations of the framework. The most important limitation is related to the endogenous representation of the institutional change processes. Although it is possible to include institutional changes into the analyses in the form of scenarios as in the case of ElectTrans, or very abstract endogenous indicators as in the case of WasteTrans, the framework is evaluated to be limited in terms of institutional change mechanisms. Moreover, the quantification of the mechanisms related to the behavioural identities of the actors is observed to be one of the most challenging processes. As it is demonstrated in the WasteTrans case, such a limitation can be overcome to an extent by supporting the conclusions with extensive sensitivity analyses. A second practical problem is related with analyses using models rich in detail and low in the aggregation (e.g. ElectTrans). A proper analysis of transitional dynamics requires considering a vast number of scenarios, as well as social and technological uncertainties. Therefore, novel experimental analysis approaches that rely on more extensive sets of simulations are needed to supplement the use of the framework in such detailed modelling cases.
Samenvatting

Dit onderzoek behoort tot de verzameling van analytische studies van transities. Het richt zich op de dynamiek van transities en op manieren om deze dynamiek te onderzoeken, in het bijzonder in de context van socio-technische systemen. Het onderzoek is in belangrijke mate gedreven doordat kwalitatieve aanpakken in het verklaren van transities niet blijken te voldoen. De belangrijkste onderzoeksdoelen zijn de volgende:

- Onderzoek naar de potentiële bijdrage en beperkingen van simulatie-ondersteunde analyse voor het bestuderen van transitiedynamiek.
- Ontwikkeling van een algemeen conceptueel raamwerk voor simulatie-ondersteunde analyse om de transitiedynamiek in socio-technische systemen te bestuderen.

Het eerste deel van het onderzoek bevat een methodologische beschouwing van simulatie-ondersteunde analyse. Deze is gericht op verschillende aanpakken, technieken en toepassingen. Het tweede deel van het onderzoek gaat over het actor-optie raamwerk dat ontwikkeld is als algemene basis voor simulatie-ondersteunde analyse van transitiedynamiek. In het derde deel van het onderzoek wordt de bruikbaarheid van het actor-optie raamwerk bestudeerd aan de hand van drie modelstudies.

Deel I: Simulatie-ondersteunde analyse voor het bestuderen van transities

In analytische transitiestudies is men geïnteresseerd in het verloop van een transitie, in plaats van in statische concepten zoals de uiteindelijke toestand van het bestudeerde systeem. De systemen die in het transitieveld bestudeerd worden zijn doorgaans complexe adaptieve systemen. Deze systemen vertonen een dynamische complexiteit waarvoor analyse met behulp van kwalitatieve methoden vrijwel onmogelijk is. Deze studie staat een computationele aanpak in het algemeen en computersimulatie in het bijzonder voor, als veelbelovend voor het analyseren van de complexiteit van transitiedynamiek. Alhoewel er een uitgebreide methodologische discussie gevoerd wordt in Deel I, komen drie aspecten met name aan bod: de verschillende manieren waarop simulatiemodellen gebruikt kunnen worden voor het bestuderen van transities, de belangrijkste beperkingen van het gebruik van
Samenvatting

Simulatiemodellen voor het analyseren van transitiiedadynamiek, en verschillende manieren waarop zulke modellen ontwikkeld kunnen worden.

a. Modelgebruik voor het bestuderen van transities

Er zijn verschillende mogelijke manieren van gebruik van modellen voor de studie van sociale fenomenen. Zoals wordt beschreven in Hoofdstuk 2 zijn drie van deze manieren van gebruik relevant voor het bestuderen van transities:

- **Ontwikkeling van casus-specifieke inzichten:** Onderzoeken van plausible transitie-trajectoriën voor een bepaald socio-technisch systeem
- **Ontwikkeling van generieke inzichten:** Het bestuderen van gedragsmatige consequenties van een verzameling interacterende processen onder verschillende omstandigheden gebruikmakend van generieke modellen
- **Theorieontwikkeling en verfijning:** Evaluatie en verfijning van een voorgestelde theorie om transitiiedadynamiek te verklaren door gebruik te maken van modellen die gebaseerd zijn op de uitgangspunten van de theorie

Verder wordt besproken dat simulatie-ondersteunde analyse traditioneel alleen geassocieerd wordt met het eerste type modelgebruik. Een dergelijke veronderstelling beperkt het potentieel van de aanpak.

b. Modellerenmethoden voor het bestuderen van transities

In Hoofdstuk 3 wordt een overzicht gegeven van bekende modellerenparadigma’s die gebruikt worden om socio-economische verschijnselen te analyseren: econometrie, micro-simulatie, system dynamics (SD) en agent-based modelleren (ABM). Rekening houdend met de dominante conceptuele perspectieven en algemene doelen bij het bestuderen van transities, worden de laatste twee aanpakken als veelbelovend aangemerkt en verder onderzocht.

Gegeven de multidimensionale aard van het transitieprobleem en de variëteit aan verschillende potentieële manieren waarop een model in deze context gebruikt kan worden, wordt beargumenteerd dat het misleidend zou zijn om één enkele aanpak als *magic bullet* aan te merken. Zo is het ook moeilijk om over één enkel alomvattend model te spreken om alle aspecten van transities te bestuderen. Er wordt geconcludeerd dat het misleidend is om een algemene uitspraak te doen over welke aanpak het meest geschikt zou zijn voor het bestuderen van transities, omdat SD, ABM en hybride modellen (d.w.z. modellen die SD en ABM componenten combineren) verschillende sterke punten hebben die passen bij verschillende vraagstukken binnen het veld van transitiestudies.

c. Uitdagingen bij simulatie-ondersteunde analyses van transitiiedadynamiek

In Hoofdstuk 2 worden een aantal tekortkomingen en daaraan gerelateerde methodologische uitdagingen voor simulatie-ondersteunde analyses van transitionele verandering besproken. De belangrijkste tekortkomingen komen voort uit drie belangrijke problemen: *modelleren van het sociale, onbekendheid van toekomstige vernieuwingen, de rol van toevalligheden*. De belangrijkste implicaties van deze problemen voor simulatie-ondersteunde analyses, in het algemeen en voor de drie manieren van modelgebruik die besproken worden in Hoofdstuk 2, komen in Hoofdstuk 2.4 in detail aan de orde.
Deel II: Het actor-optie raamwerk

Deel II introduceert het actor-optie raamwerk voor het modelleren van socio-technische systemen. Gedetailleerde case studies uit de literatuur van verschillende transities en aan transities gerelateerde veranderprocessen vormen de empirische basis voor dit actor-optie raamwerk. Het raamwerk levert een verzameling van basisbouwstenen, en een verzameling verandermechanismen die daaraan gerelateerd zijn, waarmee verklarende modellen ontwikkeld kunnen worden.

**a. Basisbouwstenen van het actor-optie raamwerk**

De dynamiek van transitionele verandering in socio-technische systemen komt voort uit gezamenlijke veranderingen in de sociale en technisch-fysische aspecten van het systeem. Deze aspecten hebben hun eigen interne dynamiek en ze verschillen sterk van aard. Dit heeft tot de conclusie geleid dat, om transitiedynamiek te verklaren, de dynamiek van sociale en technisch-fysische aspecten simultaan, maar afzonderlijk beschouwd moeten worden. Eén van de bouwstenen van het raamwerk (een *actor*) wordt beschouwd als zijnde representatief voor de sociale elementen van het systeem. De toestand van de technisch-fysische wereld is zeer belangrijk voor het gedrag van de actoren in de context van een bepaalde maatschappelijke functie. De tweede bouwsteen van het raamwerk (een *optie*) bestaat uit de alternatieven voor de sociale elementen van het systeem.


**b. Verandermechanismen**

De algemene conceptuele representatie in het actor-optie raamwerk is bedoeld om transitionele verandering in termen van endogene veranderprocessen, d.w.z. *mechanismen.* Deze mechanismen zijn vooral gerelateerd aan: veranderingen van opties als gevolg van keuzes van actoren, veranderingen in de informatie die actoren hebben over hun omgeving en beschikbare opties, en veranderingen in de identiteit van actoren die hun voorkeuren bepaalt. In het onderzoek zijn 10 algemene mechanismen geïdentificeerd die onder 3 groepen geschaard kunnen worden, mechanismen die te maken hebben: met optie verandering, met actor kennis, en met actor identiteit. Deze mechanismen worden in Hoofdstuk 5 in detail beschreven.

De inductieve analyse van case studies uit de literatuur heeft geresulteerd in het conceptuele raamwerk met bouwstenen en een verzameling van mechanismen. Deze mechanismen
verklaren hoe de bouwstenen interacteren en veranderen, en daardoor de transitiiedynamiek van het systeem vormgeven. In die zin is het actor-optie raamwerk geen algemeen transitiemodel, maar het is een verzameling van modulaire concepten (d.w.z. actoren, opties, mechanismen) waarmee modellen ontwikkeld kunnen worden die case specifiek zijn of generiek op een bepaald niveau.

Deel III: Gebruik van het actor-optie raamwerk
In het derde deel van het onderzoek wordt het actor-optie raamwerk gebruikt in drie modelstudies. Daarnaast wordt besproken in welke mate het raamwerk kan dienen als een algemene conceptuele basis, inclusief de conceptuele en praktische beperkingen. Verder leveren de analyses die uitgevoerd zijn met de modellen bewijsmateriaal aangaande de uitgangspunten van het raamwerk.

Twee van de bestudeerde cases zijn historische transities: een transitie in de wijze waarop er in Nederland omgegaan is met afval en een transitie in het Britse systeem van zeetransport. De derde case richt zich op de huidige situatie in het Nederlandse systeem van elektriciteitsopwekking en de mogelijke dynamiek daarin. Zoals besproken wordt in Hoofdstuk 11.2, kan het raamwerk zonder problemen succesvol toegepast worden in deze verschillende contexten. Dit vormt een onderbouwing voor de algemene contextuele toepasbaarheid van het raamwerk. Daarnaast wordt het raamwerk gebruikt om analyses op verschillende aggregatieniveaus te ondersteunen. Daarin is het WasteTrans model het meest geaggregeerde voorbeeld, terwijl het ElectTrans model de minste aggregatie kent in termen van zowel opties als actoren. Met de drie modelstudies wordt aangetoond dat de modellen die ontwikkeld worden met behulp van het raamwerk gebruikt kunnen worden om sociale aspecten (b.v. normen, voorkeuren), aspecten met betrekking tot regulering (b.v. marktregulering, subsidieprogramma's) en technisch-fysische aspecten te onderzoeken. Zoals wordt besproken in Hoofdstuk 11.4, zijn de modellen zoals beschreven in de Hoofdstukken 8, 9 en 10 ook voorbeelden voor de verschillende manieren van modelgebruik zoals weergegeven in Hoofdstuk 2. De verschillen tussen de drie manieren van modelgebruik en de potentiële bijdragen daarvan worden verduidelijkt aan de hand van deze voorbeelden.

Het actor-optie raamwerk kent drie fundamentele uitgangspunten: het belang van het expliciet representeren van de sociale actoren, het vermijden van de aggregatie van verschillende soorten systeemelementen, en het hanteren van een beleidsrelevant abstractieniveau. Tijdens de analyse met de drie modellen is het belang van deze uitgangspunten nader onderzocht en hier wordt in Hoofdstuk 11 op gereflecteerd.

Aan de hand van de drie modeltoepassingen zijn ook de beperkingen van het raamwerk onderzocht. De belangrijkste beperking is de endogene representatie van institutionele veranderprocessen. Hoewel het mogelijk is om institutionele veranderingen in de vorm van scenario’s, zoals is gedaan bij ElectTrans, of als zeer abstracte endogene indicatoren zoals bij WasteTrans, is het raamwerk beperkt in termen van institutionele verandermechanismen. Daarnaast is de kwantificering van de mechanismen die gerelateerd zijn aan het gedrag van actoren één van de meest lastige processen. Zoals wordt aangetoond in de WasteTrans case, kan met een dergelijke beperking in zekere mate omgegaan worden door de conclusies te ondersteunen met uitgebreide gevoeligheidsanalyses. Een tweede praktische probleem hangt samen met het gebruik van modellen die rijk in detail zijn en een
laag aggregatieniveau hebben (b.v. *ElectTrans*). Een goede analyse van de transitiedynamiek vereist een enorm aantal scenario’s. Dit betekent dat nieuwe experimentele analysemethoden nodig zijn om bij zulke gedetailleerde modelleerstudies het gebruik van het raamwerk aan te vullen.
Samenvatting
Acknowledgements

The four-year period during which I had been working on this book was an invaluable personal experience. While delving into the transitions topic was an academic challenge since it was a whole new research domain for me, moving to a whole new country was certainly a social one. It would be misleading to say that it was all easy and happy. Put most difficulties aside, many days I found myself speaking to clouds for even a short opening for sunlight and a piece of blue sky. However, it would certainly be much harder and much less enjoyable without a set of special people, who deserve to be acknowledged.

Firstly, I would like to thank Wil and Els; before anything else, for their trust in me for this project, and the freedom they gave while working on it. Without Wil’s ‘supportive criticality’, it would not be possible to bring this dissertation to its current quality. I am certain that this research would be far away from completion and less sound, and I would have much less publications by now without the supervision of Els. She was the one that kept me moving, and moving in the right direction. Acknowledging their importance just for this research would be unfair to them. They have not just been promoters, but also mentors for me during these four years: their contributions go beyond the contents of this book, and have permanent signs in my identity as a researcher and a lecturer.

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It was an amazing coincidence that one of my closest friends, Pınar, had been living in Rotterdam when I moved to the Netherlands. I am grateful to her for all those guided-tours, insider tips about the Dutch social and bureaucratic system, tennis lessons, Stalles-times and her hospitality.

Ceyhun has been a great companion during most enjoyable times I had in the Netherlands. I have been missing our Delft meetings, long Sunday BBQs, and many ridiculous situations we found ourselves in. You had been a good friend before those years, and now you are more like a brother to me.

My dear friends, and my dear paranymphs Elvin and Özgür: anybody who knows me close enough, most likely knows them also. This is because we have been more like inseparable parts of a whole, rather than just three friends. Having three very different personalities, I think we complement each other and that is the key to our strong bonding. I am full-heartedly grateful to you for being there during my happy, but more importantly, angry, stressed, depressed, sad, and confused times. Being the analysis and planning freak of the trio, I am glad that I came to the gathering during which I met you both in September 2006.

It is not possible to find the right words to express my gratitude for my family. It goes without saying that it was not easy to be away from my mum, dad, and Gökşen. I always felt their support besides me. Without that, I would not be standing where I am, and more importantly be who I am right now. Their understanding, support and appreciation have been invaluable. I am truly proud of having their traces in my personality.

I saved my final words for a beautiful lady. I am truly thankful to Zeren, as seamen have been thankful to Polaris* for ages: thank you for helping me to set my bearing by appearing out of nowhere when the sea of ideas were rough and finding my way was not easy. Thank you for being the brightest one in my skies.

2010, Delft

* Also known as the Northern Star, or the Pole Star.
About the Author

Gönenç Yücel was born on the 11th day of the 11th month of 1977, in Bursa, Turkey. He received his B.Sc. degree in Industrial Engineering from Boğaziçi University (Istanbul), and later, joined Alarko Group of Companies as a system analyst. Deciding to pursue an academic career, he returned to Boğaziçi University in 2001 for his graduate studies, where he obtained his M.Sc. degree in Industrial Engineering. After two years as a Ph.D. student in Boğaziçi University, he moved to the Netherlands to join the Policy Analysis section in Delft University of Technology for the Ph.D. project that eventually led to this book.

Simulation methodology and simulation-based (policy) analysis were the core topics throughout his graduate studies. Despite coming from a technical engineering background, Gönenç especially enjoys delving into complex problems in the context of social and economical systems. In a sense, he can be characterized as a wanderer in social sciences with an engineering formation and toolset. The research on analyzing transition dynamics is the latest example of such an effort.

During the times when he is away from his computer, he enjoys walking around with his camera, finding peace underwater, playing basketball, trying to fix mechanical stuff and cooking for friends.

For more information about the author:
http://www.gyucel.net
Publications

Papers in Refereed Journals

Papers in Refereed Conference Proceedings
Transition can be characterized as long-term structural changes in the societal systems, through which the way these systems function change significantly. Both the scope and extent of change, and the nature of the societal systems make transition processes a complex dynamic phenomena to understand.

This study explores both methodological and conceptual issues in order to contribute to the ways transitions are analyzed. On the methodological frontier, the book investigates different forms of simulation-supported analysis. On the conceptual frontier, the study focuses on structural and behavioral similarities among socio-technical systems in order to develop a general modelling framework that can serve as a conceptual basis for simulation-supported analyses. Additional to introducing the developed framework, i.e. the actor-option framework, the book also presents a set of modelling studies that are based on it.

Analyzing Transition Dynamics
The Actor-Option Framework for Modelling Socio-Technical Systems

Gönenç Yücel

Invitation

You are cordially invited to attend the public defence of my PhD dissertation and the reception afterwards.

Thursday, 9 December 2010
12:00 Introductory presentation
12:30 Formal defence

Senaatzaal of the Auditorium (Aula)
Delft University of Technology
Mekelweg 5, Delft