

Agent-Based Modeling of Energy Infrastructure Transitions

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Abstract—Transitions emerge over time as fundamental change of large-scale socio-technical systems such as energy infrastructures that are the backbone of society. To date, however, the body-of-knowledge on energy infrastructure transitions is largely descriptive. Transition management, however, does have a prescriptive character – not only can we understand transitions, we can also shape them. This implies technical system design is augmented with policy, regulation, R&D strategies: some coherent all-inclusive set of transition instruments or transition assemblage. We conjecture a transition management strategy may equate to collaborative design of such a transition assemblage. Using foundations of complex systems theory, agent-based modeling, engineering and policy design scenario analysis, design of experiments and statistical data analysis, a modeling framework has been developed that enables ex-ante assessment of alternative transition assemblage design-alternatives.

I. INTRODUCTION

TRANSITIONS emerge over time as fundamental change of large-scale socio-technical systems such as energy infrastructures, which serve as the backbone of modern industrial societies. In transitions, change involves both the structure and the content of physical systems, their interconnections and in the body-of-rules and institutions that govern actor behavior and decision-making. In-depth understanding of transitions may enable transition management. What is lacking, however, is a basic understanding of the socio-technical design space and the complexity of and the uncertainties involved in bringing socio-technical systems or parts thereof into being.

Transitions typically span decades wherein the combination of external influence, actor behavior and actor interaction is dynamic and complex. Consequently, elucidating suitable design variables available to shape transitions is difficult and may be impossible. In transition and transition management literature, the focus is on descriptive case studies on past transitions [1-4]. However, as we have argued elsewhere [5, 6], where description leads to understanding, transition *management* implies that transitions should and can be steered and shaped. Something, a coherent assemblage of policies, regulations, R&D strategies, financing etc. is being *designed*. We define a *transition assemblage* as the

all-inclusive set of transition instruments. The effectiveness of such transition assemblage designs is expressed as *the likelihood of meeting the designers' objectives*. Since transitions are subject to huge complexity (the impacted system itself is complex), it may be seen that elucidating transitions of energy infrastructure systems is difficult if not impossible. We conjecture that Agent-Based Models (ABMs) are needed to assess the performance of designs for transition assemblages in the energy domain. This paper builds on that argument by presenting a framework for the use of ABMs as models for transition.

The structure of this paper is as follows: first, we elaborate on designing system transitions of large-scale socio-technical systems (λ -systems) [8]. Second, we demonstrate ABM is a necessary tool for assessing transitions in energy infrastructure systems. Third, a framework is presented for developing ABMs to be used to support transition assemblage design. The main aspects addressed are λ -system representation, modeling of exogenous scenarios, exploring design alternatives for system transitions, visualizing system evolution and impact assessment. The discussion includes a variety of examples and focuses on the degrees of freedom that the framework explicates for modeling exercises. The paper ends with conclusions and an outlook.

II. DESIGNING SYSTEM TRANSITIONS IN LARGE-SCALE SOCIO-TECHNICAL SYSTEMS

A. Transitions of λ -systems

Infrastructures contain many interdependent components: many different actors who have specific goals and means to reach them, and technological subsystems with limited capabilities. Λ -systems are evolutionary, they exhibit path-dependency and lock-in; options in the future are shaped by current choices as well as current options have been shaped by the past. The λ -systems we observe today were not designed as such, they evolved to their present state [7, 8]. Therefore, their technological components may not be equipped to meet present needs such as sustainability, reliability, flexibility and affordability, which affects the policy design process. This results in true complexity, because (1) changes in technical components of λ -systems often only materialize when changing preferences or perceptions of stakeholders lead to new policy, strategy and decisions; and (2) in any cycle of policy design or strategy formulation with time an improved system is intended. (3) the changes involved may materialize at a time perceptions and preferences have changed

Manuscript received April 15, 2008.

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With time, this process may imply a change of system structure, fundamental change, and hence must be labeled a system transition (see Fig. 1). A system transition is therefore by definition an emerging property of a λ -system.

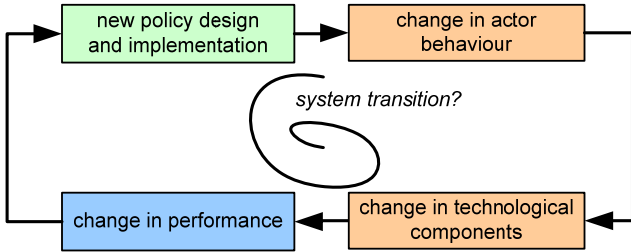


Fig. 1. From policy design to a change in performance in λ -systems.

B. Policy design should incorporate System Transitions

Policy makers face the challenge to design effective policy in and for λ -systems [9-11]. The energy infrastructure is clearly a λ -system: actors have been liberalized and competitive tasks (power and natural gas generation and retail services) were unbundled from monopolistic tasks (grid and pipeline operators); the sector is embedded in and strongly connected to several markets, i.e. fuel, emission-trading and spot markets. All the actors active in these markets have their own objectives and means to realize them. The government has to set the rules of the game using policy and regulation as main instruments in such a way that actors by realizing their goals will have optimum behavior according to the policy makers set of objectives.

If policy intends to lead to structural change in a λ -system – for whatever reason – it is likely that a *system transition* is needed. We will use a definition for system transitions (see also Fig. 1): “A system transition is structural change in both technical and social subsystems” [6]. The policy needed for structural change is therefore only effective when it initiates a transition to an optimal end state. In addition to requirements for the end-state, there might be requirements or objectives for the pathway of the transition itself. Incorporating the transition pathway and end state adds a new dimension to the challenge of policy design.

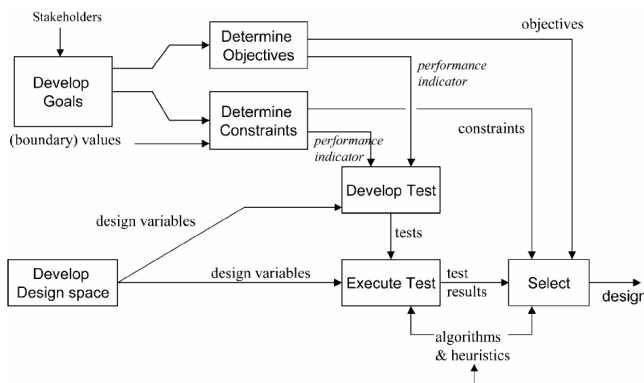


Fig. 2. Conceptual model of a design process [12].

C. Knowledge gaps in the design of System Transitions

Based on design literature [7, 13, 14] and the steps defined in a design process (see Fig. 2), a number of knowledge gaps have been identified on the design of system transitions. Since these have been described in detail elsewhere [5, 6], we will only summarize them here. A design of a system transition encompasses a transition assemblage that is estimated a certain performance, based on transition tests (see Fig. 3).

First, there is a need for transition indicators, which should unambiguously state the performance of system transitions – their pathway and their end-state – according to the objectives and requirements of its designer.

Second, there is a need for clear understanding of transition instruments: the design alternatives, based on design variables in order to come to the largest variety of possible designs for system transitions.

Third, one needs to be able to test the different designs with suitable tests to assess their performance, measured by the performance indicators.

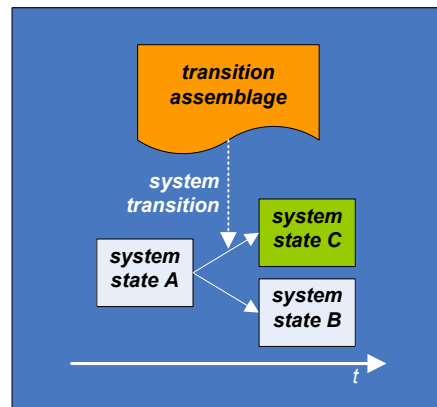


Fig. 3. Design of a transition assemblage, based on [5].

III. PROPOSED FRAMEWORK FOR AGENT-BASED MODELS OF TRANSITIONS IN ENERGY INFRASTRUCTURE SYSTEMS

Testing the performance of system transitions is a difficult task since the system under study is complex. We believe that it is not sufficient to rely only on traditional assessment methods, such as top-down models and economic optimization models. Those models often exhibit hidden, implicit underlying assumptions, for example ‘being equipped for homogenous actors only’. For testing the performance system transitions, one rather needs to outplay the evolution of λ -systems under different transition assemblage design-alternatives. We conjecture that Agent-Based Models (ABMs) are needed to assess the performance of transition assemblage designs for energy infrastructure systems. They fit the structure of λ -systems: decision-making of relevant actors can be modeled as behavioral rules of agents; the technical subsystem can be modeled physical networks of equipment and flows in agent-based models as well.

We present a framework for building useful agent-based models of transitions in energy infrastructure systems (see Fig. 4). The five main components of that framework are system representation, exogenous scenarios, transition assemblage design variables, system evolution and impact assessment. The rest of this section encompasses the discussion of these five components.

A. System representation

This framework intends to use ABMs as modeling paradigm for building assessments of transitions in energy infrastructure systems. This implies that that system is represented in the agent-based model. Therefore, we will define agent-based models and agents and provide the steps to come to agent-based system representations for studying the design of system transitions in λ -systems.

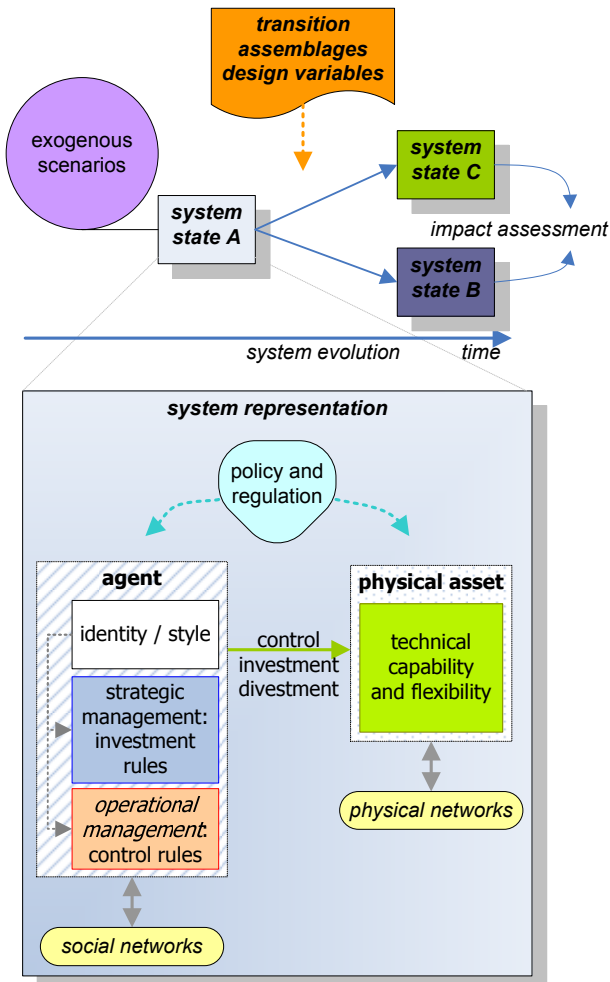


Fig. 4. Framework for assessing system transitions with agent-based models. The main components are system representation, exogenous scenarios, transition assemblage design-variables, system evolution and impact assessment.

An agent-based simulation model is often defined as “a collection of heterogeneous, intelligent, and interacting agents, which operate and exist in an environment, which in

turn is made up of agents” [15, 16]. An ABM contains a set of interacting ‘agents’ with certain properties, acting based on a set of rules, reacting upon factors coming from outside. An agent is defined as “an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives” [17]. Although in the literature different sets of properties for agents are proposed [18, 19], the core components are:

- a set of goals
- a working memory
- a social memory
- a set of rules of social engagement

In order to operationalise the system representation, one can use many tools and methods. Developing a system representation is a process that combines the collection and interpretation of knowledge about the system. The framework prescribes the structure in which this knowledge is translated into the system representation. This follows from the combination of using agents in agent-based models and chosen λ -systems-perspective.

The model developer defines a conceptual model of the system, containing all relevant elements. Those elements are implemented by formalizing the identity and decision-rules of agents and the properties and capabilities of physical assets. In addition, communication protocols have to be defined for agent interaction, in other words, for creating social and physical networks.

Within this framework, there are still many system representations possible. Further operationalisation is a tailored design process, specific to the domain under study and the researchers focus. Even more, it is likely that additional conventions and/or methodologies can assist that process. For instance, one can use the System Decomposition Method [8, 20-22], which is a method to formalize knowledge of actors into an agent-based model. The method prescribes that one must do this by gathering data from actors and domain experts in a structured and systematic manner. Knowledge is put into a for actors acceptable formal computer model. Next to this method, many suggestions exist to increase the efficiency of a model development process, e.g. chapter 9 of [23].

It is crucial that the system representation is compatible to answering the research questions and is in balance with other aspects, discussed below.

TABLE I
COMPLEXITY OF EXOGENOUS SCENARIOS

Level	Description	Level of complexity
1	Static parameter values	Low, little data needed
2	Varying trends	Medium, stochasticity needed
3	System dynamic models	High, system dynamics model needed

B. Exogenous scenarios

The systems under study are complex and need strict delineation in modeling exercises. The parameter space will be spanned by many parameters. Using the ideas of environment scenarios one can build a scenario space [24, 25]. The scenario space can have one of several levels of complexity. Table I presents an overview of those levels.

1) Static parameter values

The easiest way is to vary parameters between runs only. The price of a certain good may be given a particular value in each simulation run, which for each simulation run fall within some range. In this case the need for data is limited. Only the minimum, maximum and interval to be used need to be set for each parameter. The minimum and maximum values may be seen to reflect the parameter value uncertainty.

2) Varying trends

To model scenario parameters as true continuous trends is more difficult and data-intensive. At this level we would need a representation of a good's price trend. This implies we need a start value and a change pattern. This requires additional parameters such as the selection of probability distribution and properties. However, this approach would enable the use of more realistic scenarios. Uncertainty is modeled by the range of parameters values that define the scenario trends.

3) System dynamic models

Finally, one can build or use existing system dynamic models (SDMs) to generate exogenous scenarios. SDMs are a collection of differential equations and are often considered a contradictory modeling paradigm to ABMs, since ABMs are discrete and SDMs continuous [26, 27]. We believe, however, that we can combine both paradigms into a hybrid to use best of both worlds. A single SDM may generate multiple scenario parameters. Again, this may be more complicated than varying trends only, as this approach not only leads to software requirements but also requires different modeling skills and more knowledge on related parts of the system. Using SDM to modeling exogenous scenario parameters must be considered if multiple scenario parameters are strongly correlated and in the case appropriate, well-designed SDMs are available.

TABLE II
TRANSITION ASSEMBLAGE DESIGN VARIABLES

Level	Description	Level of complexity
1	Implicitly modeled	Low
2	Fixed system parameter	Medium, model needs responsiveness
3	Exogenous scenario parameter	Higher, model requires flexibility
4	Endogenous system parameter	High, model requires regulatory adaptability

C. Design variables for system transitions

Similar to exogenous scenarios, different levels of

complexity exist for modeling the transition assemblage design. Table II presents an overview of those levels.

We conjecture that for adequate evaluation of transition assemblage designs, one should aim to modeling at level three or four. This can be achieved by starting a modeling exercise at level two, but level one should be avoided, since it might disable reusability. One should take notice that these levels are not exclusive. Note that different levels of policies and regulations can be in one model at the same time.

1) Implicitly modeled

In this case, the structure of the model accommodates a certain policy and regulation. The assemblage is a fixed set of policy and regulation, the setting of which in the model is implicit. Since the set is fixed, it may prove hard or impossible to adapt to changes. Therefore, it is recommended not to apply level one policy and regulation in transition models. Unfortunately, however, level one policy is often the case for models reported in the literature, which limits their reusability. The very selection and design of policy and regulation de-facto is a transition assemblage design variable. When one has not taken this into account while building transition models, alteration of policy or regulation to investigate different assemblage design alternatives is impossible without building a new model.

2) Fixed system parameter

When policy or regulation is a fixed system parameter, the model needs to be able to respond on this parameter setting during the simulation. Translated to agent-based models this implies that agents base their decisions on this policy setting and assume (or are uncertain about the) stability of this policy setting. The policy is exogenous to the model, since it is unrelated to other systems properties.

If one incorporates a level two design variable, it is possible to upgrade to level three by adding agents' responsiveness to other policy values, keeping the model structure intact. Therefore, it is advised to start out with policy modeling at least at level two. Later one can upgrade to level three using the same model.

3) Exogenous scenario parameter

The third level for modeling policy is as a scenario parameter that is exogenous to the system in transition. In this setup, policy is modeled as one of the three levels of scenario parameters – varying parameter values between runs, varying trends between runs, or based on system dynamic models – all with their advantages and disadvantages (see section III B).

Only at this level and upwards, it is possible to vary the modeled policy or regulation in order to derive and test different transition assemblage design-alternatives. Therefore, this is the lowest level that a modeler should aim for when modeling policy in this framework. However, as stated above, one may start with fixed system parameters (level two) as this will not limit model expansion.

4) Endogenous system parameter

At this level policy development is modeled as an

endogenous system parameter. This implies the government is an actor included in the system representation who decides during a simulation run on particular policy and regulation. Government decisions are based on the systems state and the decision-rules used to model government behavior. Since the system state depends on agents action upon implemented policy, the government acts based on agent behavior. Therefore the policy setting is an emerging property of the system.

For modeling policy and regulation as an endogenous system parameter, one needs all relevant connections and interdependencies with other parameters in the model. This may prove to be difficult, because data on governments' responsiveness under different conditions is lacking. It may be possible to model remaining uncertainties as (level three) exogenous scenario parameters. By the combination of those two, one can have a model in which the policy is the result of the systems state, the decision-rules of the government and exogenous parameters. This will lead to robust evaluations of designs, since it acknowledges the evolution of policy as well as uncertainty in governments' actions.

D. System evolution

By the actions of agents the system will evolve over time. They act as part of the system, by reacting on exogenous scenarios and endogenous parts of the system using their decision rules. Since the agents depend on actions of other agents, system level properties and system behavior are emergent. As stated above, policy can also be emergent if it is modeled endogenously. Since uncertainty is modeled as variety in parameter settings, the system evolution of one simulation is not a solid prediction of the future of a system. One needs an impact assessment by using different system evolutions at different locations in the parameter space.

E. Impact assessment

Together, the above notions are the necessary ingredients for the impact assessment of the design alternatives: how to decide what transition assemblage design is preferred. The impact assessment has to encompass a well-designed set of experiments and a solid analysis of their results.

1) Parameter sweep: experimental design

In order to assess and compare the performance of different transition assemblage design-alternatives, one can use literature on design of experiments, e.g. [28-30]. An experimental design is the way in which different parameters of the model are varied between different model runs, in other words how the parameter sweep is set up. Classical methods include factorial designs, in which the parameters are varied independently [31]. Within the class of factorial designs, the main design is full factorial, a design in which the experiments take on all possible combinations of the levels of the parameters. Usually, each of the parameters has only two different values.

One can opt for a fractional factorial design, which takes a subset of the experiments in a full factorial design if the

number of parameters is too large to be able to execute the experiments in a reasonable amount of time with the provided computational power. An efficient form of a fractional-factorial design is obtained by a technique called Latin Hypercube Sampling (LHS) [32]. This technique allows to select any preferred number of experiments where the resulting set is uniformly distributed over the multidimensional parameter space. Thus, the number of experiments can be set depending on time and computing resources available.

The use of environment scenarios [24, 25] leads to a slightly different case, although the experimental design can be seen as a different class of fractional factorial designs. Environment scenarios are a discrete number of combinations of *factors*, in which each factor is the driving force behind a number of parameters that are exogenous to the model. In other words, parameters are grouped in their variation, which leads to a smaller number of possible combinations. To arrive at a suitable variation of the values of scenario factors one may again use one of the experimental designs described. Altogether, this is a fractional factorial design that is fundamentally different to LHS, because preselected groups of parameters are varied in concert. As a consequence, the use of environment scenarios explicitly imposes the assumption that the parameters in each group are interdependent.

2) Analysis of the results: assessment methods

The raw simulation result is a full record of the state of the evolving system during all experiments in the parameter sweep. The recorded parameters should include not only the selected performance indicators, but also the input variables, in order to allow testing for correlations.

Since the parameter space is large, and modern computational power allow large sets of runs to be completed in reasonable time, this full record often is a huge amount of data. One can use visualization methods to grasp some specifics hidden in the data, but this does not lead to real assessments. Rather, statistical methods for data analysis must be used for assessing and comparing the performance of different transition assemblage designs. However, statistical methods generally are of static nature and are not capable of adequately analyzing the results. There is a need for adapting and building statistical methods to assess and compare different designs by their variety and uncertainty in evolving performance. A first example is for instance by making series of Student-T tests over time, to assess differences in means [5].

IV. CONCLUSION AND OUTLOOK

Since transitions in energy infrastructure systems are to be 'managed', we developed a framework to use ABMs as transition simulation models for the assessment of transition assemblage design-alternatives. To reflect the main components and interactions of energy infrastructure systems this framework adopts a large-scale socio-technical systems perspective and expands it to allow for modeling transitions

of and in such systems.

The proposed framework consists of a number of parts: First, the system representation is based on agent-based modeling and systems thinking. Second, exogenous scenarios use scenario analysis and/or system dynamics. Third, design variables for system transitions is based on policy making, transition literature and also reflects back to scenario analysis. Fourth, system evolution reflects complex systems thinking. Fifth, the impact assessment can be a combination of experimental design, scenario analysis, statistics, and data mining.

The framework brings together many research domains, which fits the multidisciplinary approach needed to elucidate transitions and underpin transition management. Its intention is not to limit the researcher, but rather to structure and explicate his choices, and build models that are not only useful but also reusable and modular.

To explore its applicability and use, the framework is currently being tested and elaborated upon in several case studies that will be the subject of future publications. The first case on the assessment of carbon policy impacts on the Dutch electricity infrastructure system has been finished and publications are underway [33, 34]. A second case on developments in worldwide markets for LNG is in progress.

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