Exploring Transition Dynamics: A Case-based Modeling Study

Gönenç Yücel and Els van Daalen

Policy Analysis Section, Faculty of Technology Policy and Management
Technology University of Delft, Delft, The Netherlands
g.yucel@tudelft.nl, C.vanDaalen@tudelft.nl

Abstract. The concept of 'transition' can briefly be defined as long-term structural change processes spreading over several aspects of a societal system, such as, culture, technology, institutions and infrastructure [1-5]. The complex nature of systems going under transition makes utilization of quantitative simulation models in exploring transition dynamics a potentially fruitful approach. This study builds on a historical case study for the development of a model, which captures the important underlying dynamics of the process. Following the construction of the model, it is used to experiment a set of hypothetical scenarios. The model developed for the selected historical transition relies on the Framework for Modeling Socio-Technical Transitions (FMoST), and focuses on the feedback interactions between the decisions of relevant actors regarding utilization of available options (i.e. means of fulfilling the socio-technical function), and the attributes of these options. The dynamics observed in the experimentation phase provide some insight about underlying dynamics as well as some of the previously made arguments about transition dynamics and modeling for transition.

Keywords: Socio-technical transitions, simulation, steam-ship transition

1 Introduction

The concept of 'transition', which can briefly be defined as long-term structural change processes spreading over several aspects of a societal system, such as, culture, technology, institutions and environment [1-5], is attracting significant attention due to the growing need for shifting to more sustainable modes of functioning in various important socio-technical systems, e.g. energy, transport, health, etc. Understanding the underlying dynamics of these long-term processes is vital in designing more effective policies.

Given the interconnected nature of the social, ecological and technical (physical) components of socio-technical systems, and the multi-dimensional and multi-actor nature of transitions, understanding the dynamics of such processes or at least developing some useful insights relevant to policy design is almost impossible by just relying on qualitative analysis. This complex nature makes utilization of quantitative simulation models in exploring transition dynamics a potentially fruitful approach.

In a wider research context, which also includes this individual study, it is aimed to utilize simulation models in order to explore transition dynamics. In doing so, the models, which in a way represent dynamic hypotheses regarding ongoing/historical transitions in terms of components and their interactions involved, are used as experimental test grounds to explore plausible consequences of differing conditions and system configurations. In line with this overall objective, this study builds on a historical case (i.e. transition to steam-ship based naval transportation in Great Britain) for the development of a model, which captures the important underlying dynamics of the process. Following the construction of the model, it is used to experiment with a set of hypothetical scenarios.

In the following section a brief summary of the selected historical case is given. In Section 3, the main aspects of the model will be introduced briefly, and this will be followed by the section in which output of the model in the reference run as well as scenario runs are discussed. The last section is reserved for discussion and conclusions.

2 Overview of the Historical Transition Case

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 from a transition perspective can be found in [3]. Apart from that, more specific aspects of the process and technologies that are involved can be found in [6-9].

The selected historical transition takes place in the naval transportation system of Great Britain. As a result of this transition, which took place between late 18th and early 20th centuries, the dominance in naval transportation shifted to steam-ships from the formerly dominant option of 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, due to short-comings such as range, operating cost and performance in open seas, the utilization of the steam-ships was limited mainly to transportation on inland waterways.

Three main markets existed for these ‘competing’ transportation options; merchandise, passengers and mail. Being independent of winds, the steam-ships were much more reliable in terms of travel times, and also they were faster on average. With those characteristics, they were quite desirable for mail and luxury passenger markets. However, their technical shortcomings as range (due to coal supply) and operating cost were balancing the advantages and probably preventing their further utilization apart from inland water transportation. Especially range was a significant problem for long-distance merchandise to/from North America or 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 steam-ships. Parallel to this, significant technological developments were realized. These were partially due to the exogenous developments attained in other fields where steam engines were used (e.g. increase in fuel efficiency). On the other hand, wider utilization of steam-ships also resulted in some gradual improvements. Learning-by-doing and economies of scale can be proposed as potential mechanisms of these improvements. Especially the construction of refueling stations, and the improvements in the fuel efficiency made the steam-ships a viable option even in long-range transportation. These developments during the transition period put the steam-ships in a strong competitor position against the sail-ships.

Toward the end of the transition period, the steam-ships were considered to be superior to 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 as low value freight transported to long distances. To summarize the change in figures, the Great Britain naval transportation market in which 95% of the vessels (in terms of tonnage) were sail-ships around 1850s, had transformed into a steam-ship-dominated state by 1910. At that point in time, only 5% of the vessels were sail-ships.

3 Model Description

A quantitative simulation model of the steam-ship transition has been developed. This model relies on the *Framework for Modeling Socio-Technical Transition*s (FMoST), which is partially introduced in [10, 11]. This framework defines transitions as significant changes in the means (e.g. steam-ships, sail-ships, etc.) used to fulfill a socio-technical function (e.g. naval passenger and freight transportation).

In order to capture the dynamics of such a change, the framework focuses on the feedback interactions between the decisions of relevant actors regarding utilization of available *options* (i.e. means of fulfilling the socio-technical function), and the attributes of these *options,* which can be seen as a variant of the social feedback process labeled as “actor structuring loop” by Burns and Flam[12] (see Fig 1). In other words it focuses on how *actors* decide based on *option* attributes, and how *option* attributes change based on *actor* decisions. These feedback interactions are maintained via various dynamic mechanisms, of which the relevant ones will be introduced in the following sections.

Focusing on *actor* decisions as the main driver of change, FMoST categorizes actor-groups based on the nature of impact of their decisions on the system. According to this categorization four actor-roles are identified [10];

- *Providers:* Actors who provide and maintain the means for fulfilling the societal function and whose decisions influence the means of provision (e.g. infrastructure). This includes maintaining the infrastructure, supplying a certain artifact, investment in new options, etc.
- *Regulators:* Actors whose preferences regarding the means for fulfilling the identified function influence their use via regulations (e.g. a government agent providing subsidies or taxes). The decisions of these actors have an impact on, for example, laws and regulations regarding available options.

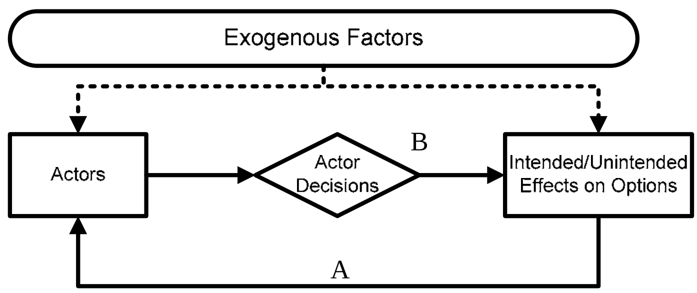

Fig 1. ‘Actor structuring loop’ of Burns and Flam[12], adapted to FMoST concepts

- *Practitioners:* Actors who actually use the available means that are regulated by regulators, provided by providers and supported/opposed by opinion groups for fulfilling the societal function of concern.
- *Supporters:* These actors' preferences regarding a means for fulfilling the identified function may influence the way it is perceived as more or less favorable by other actors. However, their influence on the perception of the means, or the means themselves is indirect. The decisions of this actor group to support or oppose an option at the most general level are thought to be influencing the social perception regarding that option.

In the historical case being modeled, only two of these *actor-roles*, i.e. *practitioners* and *providers*, are found to be relevant[3]. Under each actor-role, it is also possible to identify several actor-groups with differing preferences/priorities regarding the naval transportation needs. Hence, the model recognizes seven *practitioner*, and two *provider* groups. These actor-groups with their corresponding priority levels for different aspects of the naval transportation function are given in Table 1 and Table 2, respectively.

Via introducing heterogeneity among *actor-groups* regarding preferences/priorities for different aspects of the function, it is aimed to capture different dynamics of *option* choice among the *actors*.

Table 1. *Practitioner* groups and their priority levels[1]

	Consistency in travel times	**Speed**	**Cost**	**Range**
Merchant - Type I *(Long distance, Low Value Freight)*	Low	Low	High	High
Merchant - Type II *(Long distance, High value freight)*	High	High	Medium	High
Merchant - Type III *(Short distance, Low Value Freight)*	Low	Low	Medium	Low
Merchant - Type IV *(Short distance, High Value Freight)*	High	Medium	Low	Low

[1] The ‘priority levels’ indicate how important an aspect of the naval transportation issue is for that particular actor. For example, a ‘low’ priority indicates that actor is indifferent to differences among options regarding that particular aspect.

Government Postal Service	High	High	Low	High
Luxury Passengers	High	High	Low	High
Emigrants	Low	Low	High	High

Table 2. *Provider* groups and their priority levels

	Investment Cost	**Demand**
Individual Owners	High	High
Large Shipping Companies	Medium	High

3.1. *Actors* Choosing Among *Options*

Each *actor* is conceptualized to control a certain amount of *resource* in the model. For the case of a *practitioner* this resource can be thought of as the amount of the freight that *actor* is willing to ship. For the *providers'* case, the *resource* represents the investments available to be made in different *options* by the *actor*. Based on the information the actor has about available shipping *options*, it modifies the desired level of resource allocation for each *option* (i.e. desired percentage of the freight that the actor is willing to ship with means of a particular option).

As already mentioned, the *actors* use the most recent information they have about available *options*, which is not necessarily precise. The precision of the information improves over time representing the diffusion of information among actors, and also this improvement process speeds up as a consequence of direct experience with the *option* (i.e. the more the *actors* utilize an *option*, the faster they learn about the *option* attributes). This 'learning' mechanism is depicted in a simplified representation in Fig 2;

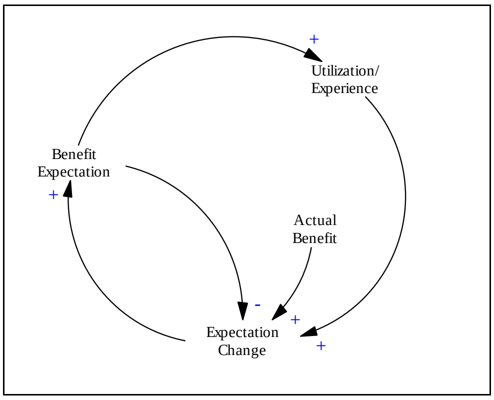

Fig 2. Feedback diagram for the learning(about)-by-doing mechanism[2]

[2] 'Benefit' is conceptualized as a sort of utility value attributed to each option based on priorities of the actor, and the attributes of the option.

Although agents are constrained by the precision of the information they have during the decision making process, they are rational decision makers in the sense that they consistently have an inclination towards allocating more resources to the *option* that serves their preferences best.

3.2. Effects of *Actor* Decisions on *Option* Attributes

One aspect of interaction among actors and options is how actors change their decisions based on option attributes (A in Fig 1.). The other side of it is how these decisions affect option attributes (B in Fig 1.). In the case being modeled, three major mechanisms via which actor decisions alter option attributes can be identified. First two mechanisms can be grouped under the category of 'technological development', corresponding to improvement in the attributes of the options with the terminology used in the model.

- <u>Resource-driven development:</u> As mentioned before provider resources represent the investment flows in the model. According to this mechanism, increased resource flow towards a particular option initiates/speeds up the technological development for that option. Such an effect is assumed to be due to 'learning-by-doing' on the provider side and also more R&D efforts driven by more resources.
- <u>Fight-back reflex:</u> This mechanism represents the initial reaction of the actors, who heavily rely on an option, in the vicinity of a competing new option. It represents the efforts of the providers to improve the dominant option in order to compete with the upcoming new option. The mechanism is basically triggered when providers recognize a significant market loss. Such mechanisms are discussed in diffusion of innovations context[13], but rarely included in the quantitative models[14-16]. However, in the case being modeled existence of such a mechanism is clearly emphasized and referred to as 'sail-ship effect.'[3, 17]

The third mechanism is the economies-of-scale mechanism, according to which wider utilization of an option yields improvement in some of the attributes. In this particular case, cost per distance and investment cost per capacity are assumed to be influenced by the economies-of-scale mechanism.

3.3. Structure of the Model

Basically the model integrates the basic mechanisms mentioned in the previous sections, and aims to explore the dynamic consequences of concurrent action of these mechanisms driven by multiple heterogeneous agents. In order to provide a better understanding about the implementation of these mechanism and model behavior, a time-sequence figure depicting the processes activated during a time step of the model is given in Fig 3**.**

When	Who	What	How
t(0)	model	initialize(inputFile)	▪ Read the model instance input file (i.e. *inputFile*) ▪ Create N_{pract} number of *practitioners* ▪ Create N_{prov} number of *providers* ▪ Create N_{opt} number of *options*
t(i)	*practitioner*	valueOptions()	▪ Evaluation of the options based on the information on hand about option attributes, and preferences of the actor.
		updateDesiredUtil()	▪ Comparison of the options based on most recent evaluation ▪ Determination of desired level of utilization (i.e. percentage of load/passengers on hand to be shipped) of each option based on the comparison results.
		allocateResources()	▪ Attempt to realize the desired utilization levels. ▪ Pick a provider and allocate resources as long as the capacity of the provider allows this.
		updateInformation()	▪ Update the actor's information about the actual attributes of the options and the past actions of the other actors.
	provider	valueOptions()	▪ Evaluation of the options based on the information on hand about option attributes, and preferences of the actor.
		updateDesiredInvst()	▪ Comparison of the options based on most recent evaluation ▪ Determination of desired level of investment to each option based on the comparison results.
		allocateResources()	▪ Allocation of investment resources among options.
		updateCapacity()	▪ Updating the physical capacity of each option controlled by the actor (i.e. accounting for new investments and capacity depreciation)
		updateInformation()	▪ Update the actor's information about the actual attributes of the options and the past actions of the other actors.
	option	updateAttributes()	▪ Update the social (i.e. percentage of providers using it) and technical/physical attributes (i.e. operating costs) of the options based on former actions (i.e. level of utilization and investment) of the actors.

Fig 3. Time-sequence diagram for the model

4 Model Behavior

In the *reference run*, it is checked if the model is able to generate behavior consistent with the qualitative and quantitative information on hand regarding the historical case. The initial and final state of the actor-support distributions are given in Fig 4 and Fig

7, respectively[3]. During the reference run, it is observed that two actor-groups, i.e. governmental postal service and the luxury passengers constitute a front-runner group and initiate the transition towards the steam-ship option (Fig 5). Exogenous technological developments as well as the improvements triggered by this frontrunner group (i.e. economies of scale, resource-driven development) causes steam-ship to become more and more attractive also for other actors, and an upward move propagating among other actor groups is observed (Fig 6). At the final stage of the run, front-runner group end up at a full-support-for-steam position. Other actor-groups also seem to converge to this point with somehow higher in-group heterogeneity. Consistent with expectations, the actor-groups for which speed and regular travel times (i.e. superior aspects of the steam-ships) matter the least seem to lag behind other actor-groups in this transition process. The aggregate market share dynamics that result as a consequence of this actor-level behavior as well as the historical data are given in Fig 8. As can be seen, the fit between the historical data and model output is significant in the sense of both behavior characteristics and numeric precision.

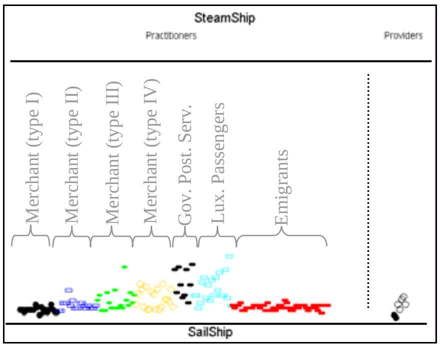

Fig 4. Actor-support distribution at t=0 (Reference run)

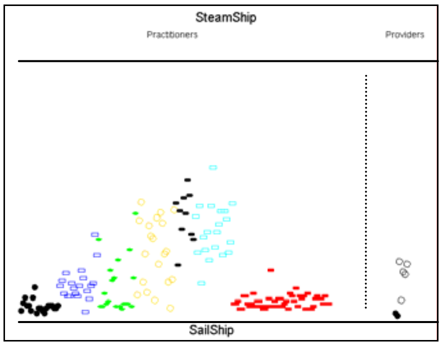

Fig 5. Actor-support distribution at t=75 (Reference run)

3 In this plot, each actor moves along a vertical line, and their position on the line represents the percentage of its resources allocated to the steam-ship option. While being at the bottom end of the vertical trajectory represents 100% support for sail-ships (i.e. 0% for steam-ships), being at the top end represents a 100% support for the steam-ship option. Each actor-group is represented with a different shape and color on the plot.

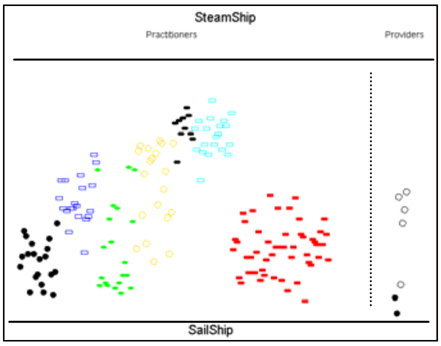

Fig 6. Actor-support distribution at t=150 (Reference run)

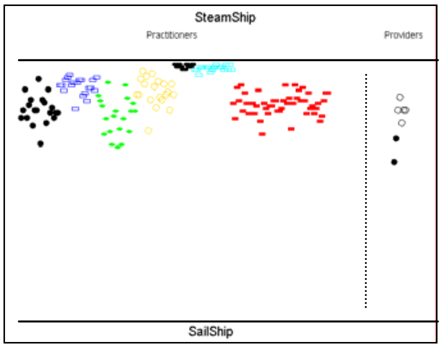

Fig 7. Actor-support distribution at t=300 (Reference run)

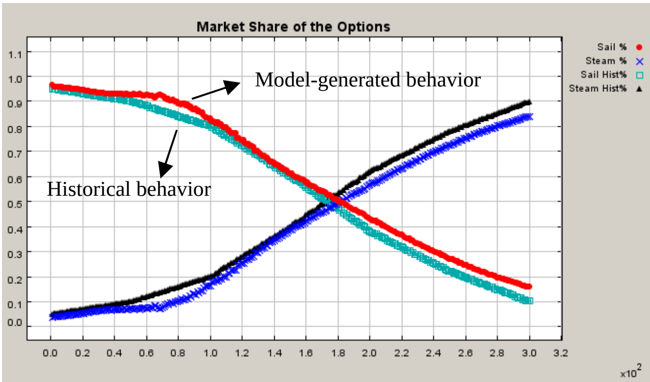

Fig 8. Historical and model-generated market share dynamics of options (Reference run)

As briefly mentioned in the reference run case, one of the key dynamics in the transition seem to be the *resource-driven development* and *economies-of-scale* mechanisms being triggered by the front-runner group. As an extension of the reference run, the ‘mass’ of this front-runner group (i.e. the share of these actors in the total naval freight and passenger market) is reduced. This change results in a weaker initial momentum, and the impact of those two mechanisms are observed to be significantly weaker compared to the reference run. This makes the transition mainly dependent on the exogenous developments of the steam-ship, hence a later and slower transition pattern is observed. The final actor-support distribution and market share dynamics are given in Fig 9 and Fig 10, respectively.

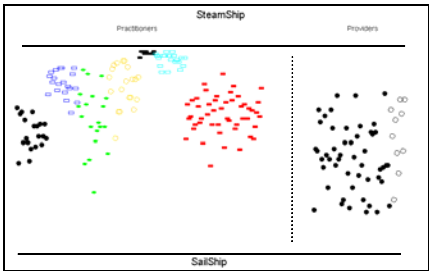

Fig 9. Actor-support distribution at t=300 (Weak initial momentum case)

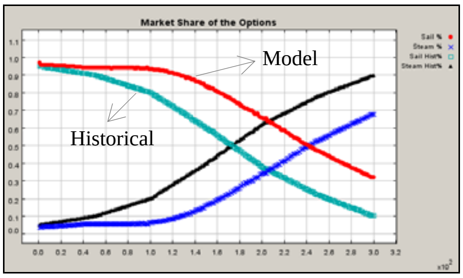

Fig 10. Market share dynamics (Weak initial momentum case)

One of the important aspects of the transition is the improvement in the range of steam-ships via development of coal stations along the routes and improvements in fuel efficiency. As a second extension, it is aimed to explore the scenario in which the improvement in the range of steam-ships happens at a limited level. The resulting dynamics, in which a dual-option end state is observed, are significantly different than the reference run. Since steam-ships fail to compete with sail-ships on long range trips, it never becomes attractive for some of the actor groups (e.g. emigrants, long distance merchants, etc.). This situation results in a much more heterogeneous actor-support distribution (see Fig 11) and a market shared among two options, without the dominance of one (see Fig 12).

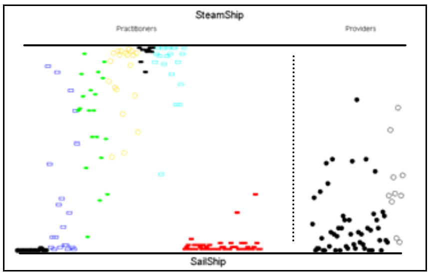

Fig 11. Actor-support distribution at t=300 (case)

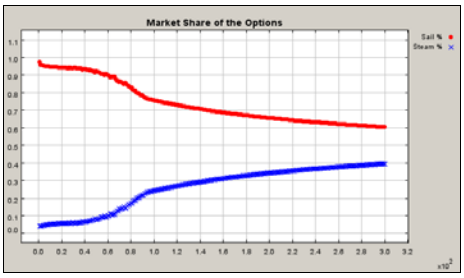

Fig 12. Market share dynamics (case)

Several other scenarios aiming to explore the possible impacts of changes regarding heterogeneity among actor-groups in terms of their preferences, delays in 'learning' and speed of change are also tested. These scenarios are discussed in [18] in detail.

5 Conclusions and Discussion

The experience of this study confirms the idea that quantitative models for transitions constitute a fruitful environment for exploring the interactions among social and technical mechanisms, and their dynamic consequences in terms of overall system behavior. Although some dynamic mechanisms are already discussed in detail in the literature on individual basis (e.g. learning, diffusion of information, economies-of-scale, etc.), it is hard to comprehend what might emerge when a set of these mechanisms interact under particular settings due to the two-way interactions among them and the non-linear nature of these interactions. As seen in this study, the combination of even a very small number of very simple mechanisms may lead to interesting and significantly different dynamics. This makes the problem hard to comprehend purely utilizing qualitative approaches and quantitative models used in the exploratory sense stands as a very effective tool in developing insights about the dynamic nature of the problem.

Based on the experimental runs of the model, the importance of the actor-group heterogeneity, i.e. the multi-actor aspect, in transition processes is affirmed. The composition of the actor-groups, which determines the possible front-runners and late adopters in a transition, makes significant differences in the overall pattern of the process. The impact of the mechanisms, like economies-of-scale, triggered by the front-runner group seems to play an important role in the pace of transitions and stands as a good point for further experimentation.

The limited number of experiments also revealed another important issue regarding transition dynamics studies, which is the importance of uncertainty of technological improvement. As seen in one of the scenarios, a very plausible scenario about the pace of development in one of the options yields a totally different system end-state. This reveals the significance of the development process, which is highly uncertain, in transitions. Due this fact, we believe that such models on transitions may contribute significantly to our understanding about the underlying mechanisms of transitions, which in turn may improve the effectiveness of our policy interventions. However, attempting to utilize such models as predictive tools for ongoing transitions will be a fallacy.

Modeling research like this, which can be labeled as preliminary transition modeling work, already provides valuable insights about the transition dynamics, and helps to enhance the approach of simulation-based exploration of transition dynamics via insights developed regarding the way models are used and the way they are developed.

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