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THE DIFFUSION OF INFRASTRUCTURE DEPENDENT TECHNOLOGIES

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Abstract:
The diffusion of infrastructure dependent technologies: A simple model

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Abstract
In order to realize the transition to a more sustainable society, changes in societal subsystems such as energy and transport are necessary. Technological substitution and the diffusion of environmentally friendly technologies are envisioned to play an important role in these changes. New sustainable technologies compete with each other and with existing technologies to become the dominant design of the future. Another barrier hampering the diffusion of these technologies is that innovations in energy and transport often require changes in infrastructures. We study this transition problem from the perspective of competing technologies (Arthur 1988), but the fact that these technologies are part of a large technical systems (LTSs) makes the competition dynamics even more complicated. This paper focuses on the interdependency between the physical components of LTS: the technical and the infrastructural components.
Literature on technological substitution and succession emphasizes the importance of network externalities and heterogeneity of agents in this process (Shy 1996, Windrum and Birchenhall 2005, Dalle1997, Adner 2003, Malerba et al. 2007). Network externalities explain for a large extent the lock-in of existing technologies which hinder the diffusion of new and sometimes superior technologies. We can learn from these models that even in presence of networks externalities, modeled as the number of users of a technology, heterogeneity of agents might lead to technological substitution of consumer goods. However, different models are needed as infrastructure development becomes crucial for diffusion, because network externalities and other determinants of infrastructure make the process to overcome the lock-in of existing systems even more complicated.
Determinants of consumer and infrastructure builder decisions can be found in the size and lumpiness of the investments needed for infrastructure development, the technological interrelatedness of the technological and infrastructural components, the spatial dimensions of infrastructure development, the competition with other (existing or new) infrastructure-technology combinations, and the fact that different types of actors select and adopt the different components of the technological system. Furthermore, the alternatives to the existing systems each have their own infrastructural requirements.

JEL - codes: O33, Q01, Q55

The diffusion of infrastructure dependent technologies

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1 Introduction

Our fossil fuel-based energy and transport system is supposed to cause environmental problems and climate change. In order to realize the transition to a more sustainable society, changes in societal subsystems such as energy and transport are necessary. Technological substitution, which encapsulates the diffusion of environmentally friendly technologies, is envisioned to play an important role in these changes. However, new technologies in the energy and transport system often require significant changes in infrastructure, which is a serious barrier for the diffusion of these new technologies. New sustainable infrastructure dependent technologies compete (with each other) to become the dominant design of the future but have difficulties overcoming the lock-in of the dominant fossil fuel-based design.
Overcoming lock-in of existing technologies is known to be difficult even for simple innovations, because a dominant design establishes standards by which also the innovation is 'measured'. Besides, users have high switching costs and benefit from network externalities established by the dominant design. For example, a user of computer software benefits when the network of users increases. However, innovations that require changes in infrastructure suffer even more from these lock-in determinants. In complex systems, or so called Large Technical Systems (LTS) [9, 10] such as the energy or transport system, infrastructure is an important component. Such systems that gained momentum are difficult to change, because infrastructure components are characterized by enormous sunk costs, which makes switching to new infrastructure unattractive to suppliers. Furthermore, new infrastructure systems consist of different and expensive components that are interrelated but selected by different actors, which might cause that infrastructure suppliers play a waiting game. Also demand for new technologies that depend on the infrastructure takes of more slowly than demand for infrastructure independent technologies. The technology demand remains small as long as infrastructure is not available over a specific geographical area. So, infrastructure dependent technologies are particularly susceptible to lock-in [11, 17, 26].

Two bodies of literature provide insights in how such changes in infrastructure dependent technologies can occur from different perspectives. From a dominant design perspective a number of analytical and simulation models study on a micro-level the mechanism that might contribute to overcome lock-in. These models are often referred to as technological substitution and succession models and focus on the importance of network externalities as the main source of lock-in and heterogeneity of agents as a core mechanism to escape the lock-in of a dominant design [1, 2, 14, 22, 27]. In these models users trade off the number of users and the quality of a technology in their decision making for one or the other technology. The old technology often has a large network of users which outweighs the higher quality of the new technology and causes that the old technology continues to be chosen. However, if users are heterogeneous and some users put a higher value on the quality of the new technology or do not care about the network size, this might lead to the start of technological substitution of consumer goods. In this paper we elaborate on these models by studying how the micro-level dynamics affect the substitution process for infrastructure dependent technologies. Because the role of infrastructure in the substitution process is understudied in these models, we use empirical insights from another body of literature to find typical characteristics of infrastructure dependent technologies and validate our model results later on.
The literature on Large Technical System (LTS) provides aggregated patterns of the substitution and evolution of infrastructure dependent technologies [10, 7]. These substitution patterns of large technological systems that have (new or existing) infrastructural and technology components is the topic of this paper. Large Technical Systems (LTS) such as the energy and the transport system consist of interacting components which contribute directly or indirectly towards a common system goal [9, 10]. The components of a LTS can be physical or non-physical; artifacts, organizations, scientific components, legislative artifacts and natural resources. This paper focuses on the interdependency between the physical components of LTS; the technical and the infrastructural components. The work of Hughes provides insights in the evolution of Large Technical Systems and the role of infrastructure development [9, 10]. Also the work of Grübler on the rise and fall of infrastructures shows clear patterns in technological substitution and succession of complex systems [7]. His work is both related to the Large Technical Systems and dominant design literature. Because Grüblers work is empirically rich and describes substitution processes on a macro scale, while the dominant design models at stake focus on substitution mechanism on a micro level, we will discuss his work in this paper from a LTS perspective.

The empirical macro patterns of the substitution of infrastructure dependent technologies described in the literature on LTS enables us to build expectations on the effect the micro mechanism found in literature on dominant design might have on the substitution of infrastructure dependent technologies. Understanding the determinants of infrastructure development and their influence on the substitution process of the infrastructural and technological components of Large Technical Systems is important for policymakers, infrastructure suppliers and other involved actors who seek to stimulate the transition to a more sustainable society. As policy makers try to stimulate infrastructure technology combinations they identify what the determinants of the new LTSs are, but they have a lack of knowledge on how these determinants affect the transition process. The aim of this paper therefore is to show how the dependency on infrastructure affect the substitution process of technologies.

In this paper, we first discuss the technological substitution and succession models in Section 2. We focus on the mechanism that might help overcoming the lock-in of dominant technologies. Then we provide a concise overview describing the literature on the evolution of large technological systems in Section 3 and identify a set of characteristics. Based on these characteristics we will show the expected effect the micro mechanisms, found in section 2, have on the substitution of infrastructure dependent technologies in Section 4. Finally, Section 5 discusses how these expectations will be tested in future work.

2 The substitution of the dominant technologies

A dominant technology is, by definition, the one that wins the allegiance of the marketplace and is the result of the interplay between technical and market choices at any particular time [25]. Often dominant technologies emerge out of the competition between a number of alternative technologies. For example, todays dominant internal combustion engine vehicles, that replaced horse carriages, won the battle with electric- and steam-powered cars at that time. The outcome of such a competition depends on the cumulation of small 'historical' events and is therefore highly uncertain and unpredictable until a technology becomes dominant and locks-in [1].

Lock-in happens through path dependent processes and increasing returns to adoption [24] such as *learning by using* [21], *scale economies*, *informational increasing returns*, *technological interrelatedness* [5] and *network externalities*. Because of these sources of increasing returns to adoption the dominant technology continues to be chosen, by both the demand and supply side, and will improve further [1], which hinders the diffusion of simple and superior technologies.

That increasing returns to adoption might lead to lock-in of one dominant design is illustrated by the simple model of Arthur [1]. In this model Arthur merged the various sources of increasing returns to adoption to one source that represent that the advantage of adoption increases as result of an increasing number of adopters. The model illustrates that in a market with two alternative technologies that adopters prefer with equal probability, one of the two options will eventually be adopted by the complete population, while the other ends up with none. Hence, society will be locked-in into one of the two technologies, but which technology will be selected is not predictable in advance.

As soon as society is locked-in into a dominant technology, technological substitution or succession is difficult.[1] Nonetheless, four models demonstrate that

[1] In case of technological substitution is the old technology replaced by a new technology that has the same characteristics. In case of technological succession is old technology replaced

even with network externalities[2] technological change might happen under the condition that agents are heterogeneous and have changing preferences [2, 14, 22, 27]. These models that do not capture infrastructure dependent technologies, but illustrate how micro processes might lead to technological substitution will be discussed in the next paragraphs. Discussing these models, we will focus on the demand side dynamics. Opposite to some of these models we are interested in the supply side dynamics of infrastructure and not of the technology. We assume that the technology will be available if there is demand for it, but that there is a lack of infrastructure for using the technology.
Most of these models attempt to explain how to overcome lock-in of a dominant design, which is different from the question how to accelerate the diffusion of new technologies. The former studies under what conditions more consumers switch to the new technology so that it replaces the old technology. The latter adds a time dimension to this question: under what conditions will more consumers shift to the new technology in order to replace the old technology within a shorter time period. Hence, as in our question, overcoming lock-in is a prerequisite in any study with regard to technological substitution. Providing an overview of the four different models gives insights in how technological substitution and succession are modeled previously, but above all it shows which mechanism help to increase the number of adopters. In section 5 we will discuss whether the same mechanism also determine the substitution process of infrastructure dependent technologies. Successively, we discuss the papers on technological substitution and succession of Shy (1996), Dalle (1997), Windrum and Birchenhall (2005) and Malerba et al. (2007).

Shy is one of the first researchers who modeled how new technologies might displace old technologies from a demand side instead of the supply side perspective [22]. In his technological substitution[3] model he demonstrates the role of varying consumer preferences in overcoming lock-in. Besides, Shy also addresses the effect other factors such compatibility and population size play in this substitution process. The consumers, in the model, repeatedly make technology adoptions based upon the utility it gains from a technology. The consumer population is divided in an old and a young consumer generation for which the utility these groups gain from network externalities and quality of a technology differs. Whether new technologies, that are assumed to be of higher quality, are adopted depends on whether consumers treat network externalities and quality as complements or substitutes. In case of perfect complements consumer utility only increases if both network size and quality increases, while consumers that threat network size and quality as substitutes can gain more utility if one of the

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by a new system that offers new characteristics that were previously unavailable [27].

[2]These models refer to the source of increasing returns to adoption, that Arthur introduced in his model, as network externalities, which suggest that the other sources of increasing returns are actually not captured by Arthur's model.

[3]Windrum and Birchenhall [27] labeled the model as a technological succession model, however Shy does not explicitly makes a distinction between these two types of technological competition.

two increases and are indifferent when network size decreases as long as quality increases.
Shy discusses three factors that might affect the speed of substitution. Firstly, he concludes that the more consumers consider the advance of quality and network size of technologies as substitutes, the faster adoption of new goods is likely to occur. When consumer consider quality and network size as perfect complements technological substitution will not take-off. Secondly, he suggest that an increase in the initial population size that has adopted the old technology intensifies the network effect and causes a decrease in the speed of substitution. Thirdly, Shy proposes that the more the new technology is compatible with the old technology, given that it is of higher quality than the old technology, the faster new technologies replace old technologies.
In contrast with Shy, Dalle focuses on the emergence of a dominant design and the role of local and global externalities in the realization of a dominant design. In his stochastic utility model [2] Dalle is following Arthur's model discussed above, in the sense that it focuses on competition between technologies that arrive at the same time on the market. Nevertheless, we can deduce some important factors, that might affect the speed of technological substitution, from Dalles' results. Dalle analyzed in his model local versus global network externalities in the situation of high or low heterogeneity among the population. Global externalities represent a world with perfect information available for all users, while local externalities arise from imperfect and asymmetric information exchange in a population of interacting users.
When a market is characterized by global externalities almost always pure standardization occurs, independent of the level of heterogeneity. So, global externalities enhances the emergence of a dominant technology, which makes substitution less likely to occur. When local externalities dominate the market, a small amount of heterogeneity will also lead to one dominant technology, but the other technology could survive in technological niches. However, if heterogeneity is strong enough, local externalities do not matter too much, making consumers choices independent. For example, neighbors who have nothing in common will not influence each others decisions. When consumers are independent in their decision making this produces equal market shares for both technologies [2] if the consumers preferences for the different technologies is equally distributed. Hence, the higher the level of heterogeneity, the less important are local externalities in the decision making of consumers.
Similar to Shy, Windrum and Birchenhall focus on the role of heterogeneity of consumers in overcoming lock-in. They explicitly model the conditions under which technological succession might occur [27]. Meaning that the new technology must overcome the network externalities enjoyed by the old technology. Both supply and demand side conditions are taken into account in their multi agent simulation model of which we will focus mainly on the demand side. The supply and demand side conditions change over time which can change the adoption behaviour of consumers. Consumers are divided in classes that each have their own utility function which is the sum of three components: direct utility and indirect utility together form the intrinsic utility and network utility. Direct

utility is, in terms of Lancaster, the utility consumers gain from the service characteristic of a good i.e. the quality. Indirect utility is the utility consumers gain from spending the rest of their budget, after buying the technology, on other goods i.e. the price. Network utility stands for the utility consumers obtain from the total number of previous adopters. The adoption decision depends on how consumer classes treat the different components of the utility function.
Windrum and Birchenhall [27] state that opposed to technological substitution, technological succession goes along with the emergence of new consumer classes with new preferences enabling the formation of niches. It is important that the intrinsic utility these new consumer classes gain outweighs the network utility. In accordance with Shy [22], they found that the probability of technological succession increases as consumers treat intrinsic utility and network utility as substitutes. In order to overcome the network externalities direct competitiveness of the new technology to the old technology in terms of quality and price is required. Even if a new technology is of higher quality, a significant higher price of the new technology might block the diffusion.
The Malerba et al. (2007) [14] model elaborates on their 1999 paper [13] and questions under what conditions new potentially superior technologies can fail to replace the old technology and how heterogeneity in demand can help to overcome lock-in. In their agent based substitution model new potentially superior technologies are initially inferior to the old technology, but will be selected by a consumer class that is willing to experiment with new products. The utility function on which consumers base their adoption decision comprises of cheapness and quality components of the technology, but also of network effects. The valuation of these technology characteristics differ for different consumer classes, due to different preferences.
Malerba et al. (2007) [14] show that network externalities are not the only mechanism leading to lock-in of a dominant technology, also consumers that are always able to select the best available technology can lead to these outcomes. The existence of experimental users or consumers with diverse preferences can break this lock-in and stimulate the development of the new technology. The speed of the diffusion of the new technology might increase if consumers would have perfect foresight, given that new technologies are potentially superior. On top of that Malerba et al. demonstrate that the higher the number of experimental users, the faster the new technology can develop, and the faster non experimental consumers classes are also willing to adopt the new technology.

Summarizing, previous research indicates that network externalities are the main source of lock-in, while heterogeneity of preferences is the most important mechanism for overcoming this lock-in. Besides, the models discussed above also learn that backward compatibility, perfect foresights, experimental users, early competitiveness, local externalities, a small initial population size and threating quality and network size as substitutes are mechanisms that stimulate the substitution process of dominant technologies. However, the role these mechanism have in the substitution process of infrastructure systems is not clear yet. Therefore, the next section analyses empirical data on the substitution process of large technological system that consists of infrastructure and technology components. Based on these findings we will discuss in section 4 how we expect that the mechanism found above will affect the substitution process of infrastructure dependent technologies.

3 The evolution of Large Technical Systems

In the previous section we discussed mechanisms that might contribute to the substitution of dominant technologies. In order to discuss in the next section how these mechanism affect the substitution of infrastructure dependent technologies, we will analyze in this section empirical data on the technological substitution and succession of infrastructure dependent technologies. Infrastructures provide services based on technological innovations that are essential for society [18, 4, 16]. We focus in this paper on infrastructure systems based on physical networks such as transportation, energy supply and communication systems. These systems can be characterized as capital intensive and durable and consist of highly interrelated components

Literature on the evolution of LTS provides insights into the role of infrastructure development in such Large Technical Systems. Large Technical Systems such as the energy and the transport system consist of interacting components which contribute directly or indirectly towards a common system goal [9, 10]. The components of an LTS can be physical or non-physical; artifacts, organizations, scientific components, legislative artifacts and natural resources. In this paper we focus on the diffusion of physical artifacts within a system (the technical and the infrastructural components) and the actors that are directly involved in the diffusion of these components (infrastructure suppliers and consumers). Systems in this paper refer most of the time to subsystems that are part of a larger system. For example the road transport system consists of roads, cars, refueling stations, automobile retailers, oil companies, repair shops, car drivers and so on. An alternative fuel systems is part of this road transport system and can be referred to as a subsystem. The fuel systems such as gasoline, diesel, liquefied petroleum gas (LPG) and Hydrogen are different subsystems that make use of the same components as the road transport system. Hence, the difference between subsystems and systems is vague and depends on how one establishes the boarders of a system.

Hughes describes the evolution and expansion of such Large Technical Systems in five (not necessarily sequential) phases in each of which the following activities are dominant: invention, development, innovation, transfer, growth, competition and consolidation. Hughes thereby describes the role of the individual actors in the growth and expansion of an LTS. As these systems grow, they acquire momentum, enabling them to develop even further. In this paper we consider that the technology and compatible infrastructure is developed to a state that is ready for market introduction and diffusion. So, this paper takes-off at the third phase of the evolution of Large Technical Systems.

Whereas Hughes focuses on the expansion of LTS, our research question ad-

dresses LTS that might be subject to decline due to emergence of competing systems or other factors. We thereby consider the environmental problems associated with existing LTS as so-called reverse salients: components that have fallen behind hamper the system performance [9, 17]: "When a reverse salient cannot be corrected within the context of an existing system, the problem becomes a radical one, the solution of which may bring a new and competing system." This competition between an existing and a new, competing (sub)system is the main subject we focus on in this paper.
Grübler, in his work on the rise and fall of infrastructures [7, 15], does also address the decline of LTS in relation to the emergence of competing systems thereby distinguishing between 3 phases: *growth*, *saturation* and *decline*. However, Grübler's work is descriptive from an aggregate perspective while, in order to answer our research question, we aim to build expectations on how the micro mechanism found in the previous section affect these aggregate outcomes. In the remainder of this section we provide a concise overview of the literature on the evolution of Large Technical Systems, thereby identifying a number of characteristics that our model should be able to reproduce in each phase of the evolution. We thereby take an evolutionary economics approach [19, 3], and identify the unit of selection, the selection mechanism and the mechanisms of variety creation that determine the dynamics for the growth, saturation and decline phase of system development respectively.

The **growth** phase which encompasses the five phases distinguished by Hughes corresponds to the familiar S-shaped curve of diffusion [20]. Grübler, based on empirical data, distinguishes two S-curves, separating the diffusion of infrastructure and the diffusion of the technology which are interdependent, but have different development patterns in time [7]. He studied the evolution of infrastructures such as canals, railroads, (surfaced) roads and in addition also the evolution of technologies using these infrastructures such as sail-, steam- and motor ships, steam-, diesel and electric locomotives and road vehicles. In the case of the diffusion of (surfaced) roads and road vehicles Grübler explicitly shows that, although both curves take off at the same time, the diffusion of infrastructure precedes the diffusion of the technology that is using this infrastructure. Hence, both curves slightly diverge over time. It is important to remark here that it covers the cumulative length of roads, which is not per definition equal to the capacity of roads. Also for other infrastructure dependent technologies it could be expected that the infrastructure development precedes the diffusion of the technology. It holds for mobile phones, the Internet, refueling infrastructure and electricity networks that in order to serve a few users of a technology a significant amount of infrastructure should be available already. Besides, these infrastructures must have high load factors for peaks in usage [9], which require that the capacity is actually bigger than the usage of the infrastructure. So, the first characteristic of the evolution of infrastructure dependent technologies is:

The diffusion of the infrastructure follows a different pattern from (and often *precedes) the diffusion of the technological component*

The interaction between these two diffusion processes is a pivotal part of the evolution of LTS. Hughes furthermore identifies an inventor-entrepreneur as the most important system builder at the beginning of the growth phase contributing to the diffusion of both infrastructure and technology. So, these inventor-entrepreneurs search for options to arrange that there is some demand with the commitment that some infrastructure will be available and the other way around. These arrangements with potential lead users can lead to the development of a niche market. The second characteristic of the evolution of infrastructure dependent technologies therefore is that:

The growth phase starts with inventor-entrepreneurs who are involved in the diffusion of both the infrastructure and the technology.

The invention and development of radical innovations that lead to a new LTS are sometimes purely technology-driven, but often occur in reaction to changes in the existing LTS. Innovations tend to cluster in time and space [6] and we may thus see the simultaneous rise of different competing infrastructure-technology combinations. Hughes [10] identifies that competing systems may emerge in reaction to the inability of the existing system to address important reverse salients. The emergence of a new technological component may lead to the emergence of a new LTS. Whether this LTS exists of all new components or involves the adaptation of components of the existing LTS depends on the compatibility of the new technological component with the existing infrastructure. This alignment and compatibility between new technologies and the existing system also is an important determinant for the speed of the diffusion of the new technology. This is in line with an earlier observation by Kemp and Volpi [12] that complex (infrastructure independent) technologies tend to diffuse more slowly. So, the third characteristics that affects the substitution of infrastructure dependent technologies is that:

Complex infrastructure technology combinations tend to diffuse more slowly.

Also technology transfer has an important role in the growth phase which involves the diffusion of infrastructure and technology to other regions or societies. The spatial diffusion of infrastructure systems is characterized by *hierarchy* and *neighborhood* effects. For example, the railways spread out from an innovation center in England to its hinterland as well as sub-innovation centers in France and Austria [7, 9]. Therefore, the fourth characteristic that affects the substitution of infrastructure dependent technologies is:

The spatial diffusion of infrastructure systems follows a national and international bandwagon effect.

As the market share of the technology grows in some regions, different types of adopters adopt the technology, that is, the population of potential adopters changes over time [12, 20]. As the number of adopters increases, prices will be reduced due to learning and economies of scale thereby making the technology attractive for other market segments. The initial cost of new infrastructure technology systems are high which clarifies why these systems often penetrate first into the high ends of the market. Edison introduced his electric light system in the financial district in order to attract shops and restaurants that could afford to use the system [9] and also the expensive railways, automobiles and aircrafts were introduced into high value market niches and only after tariff reduction into lower-value market niches [7]. Not only the costs of adopting make actors adopting at different moments in time. For example also preferences with respect to infrastructure availability differ for car drivers that visit on a daily basis the entire country and car drivers that do not leave their home town. In short, the fifth characteristic that should be captured by our model is:

Different actors adopt at different moments in time.

As systems grow further they acquire technological momentum which means that a considerable amount has been invested in physical and human capital and that a certain critical mass is reached. The system obtains direction and grows rapidly. When innovations enter this phase of momentum they often become self-sustaining [20]. Capital intensive systems such as infrastructure systems especially gain momentum as there are durable fixed assets and sunk cost that make investing in other system expensive and unattractive [10]. Before the systems reaches momentum it is thus more risky for infrastructure builders to invest in the infrastructure as it is still uncertain whether the system will become a success or a failure. The last characteristic that should be captured in the growth phase of the evolution of infrastructure dependent technologies is:

When innovations enter the phase of momentum they often become self sustaining.

The second phase in LTS development after the growth phase is **saturation.** The growth of LTS is limited, according to Grübler these limits are determined by the specific time of system development (in relation to similar systems in other countries/regions) as well as to economic, political and spatial factors. For example Grübler [7] states, using the model of Marchetti and Nakicenovic [15], that the automobile-oil cluster is in the saturation phase, which could be an indication of an upcoming decline of the automobile-oil cluster and the emergence of new technologies and infrastructures. So, the first characteristic of the saturation phase is:

Growth of LTS is limited, which is an indication of an upcoming decline of systems.

When a system is close to its limits and reaches saturation demand expansion drops. Substitution stops and only replacement of the same technology continues [7]. For example the substitution of sailships by new steamships stops and only steamships that need replacing will be replaced. Due to decreasing profits and low turnovers firms search for new investment opportunities. It is therefore no incidence that new infrastructure technology systems emerge during the saturation phase of a previous one. The increasing competition of new alternative fuel systems and uncertainty about oil prices indicate that the automobile-oil cluster is currently in the saturation phase [7]. The second characteristic of the saturation phase is:

When old systems reach saturation, the emergence of new competing systems takes-off.

While systems can maintain these saturation levels for long periods of time, most systems eventually reach the phase of **decline**. As we measure the size of a system in terms of market share of the technology or infrastructure, the saturation phase followed by a decline phase suggests that one or more substitutes emerge at that time. In contrast to the diffusion of infrastructure and technology, expected decline for technological components is faster than for infrastructure components [7]. Load factors or capacity are expected to be maintained despite a decreasing user base for the technology. Nevertheless, the durable infrastructure decays over time, given that the infrastructure is not used for a new technology, because firm are reluctant to invest more in the old system. For the decline phase it is therefore expected that:

The decline of the technological components is faster than the decline of infrastructure components.

Summarizing, we see that rise and decline of LTS is a problem of co-evolution of infrastructure and technology. Each component forms the unit of selection in a different (but related) diffusion process. When technology is the unit of selection, the main selection mechanism is the adoption decision of consumers. The investment decision by infrastructure builders forms the main mechanism of selection when the infrastructural component is the unit of selection. Mechanisms of variety creation can be explained by the fact that both system builders and consumers are heterogeneous, indicating that the selection mechanisms change over time and are different for different actors.

4 Substitution of infrastructure dependent technologies

Based on the macro characteristics of the substitution process of infrastructure dependent technologies described in the previous section, we will discuss in this section to what extent the micro mechanisms affecting the substitution process of regular technologies found in section 2 are expected to affect the substitution of infrastructure dependent technologies. The models discussed in section 2 demonstrate that heterogeneity of users, backward compatibility, perfect foresights, experimental users, early competitiveness, local externalities, a small initial population size and threating quality and network size as substitutes micro mechanisms might positively affect the technological substitution and succession of technologies. For each of these mechanisms we will discuss whether it is relevant for infrastructure dependent technologies and how we expect the mechanism will affect the substitution of such Large Technological Systems.

Heterogeneity of users implicitly has a role in most of the other mechanism that will be discussed. Therefore, the discussion regarding heterogeneity of users is limited to some general expectations. Heterogeneity of users with respect to 'regular' technologies is large and can be understood in the broadest sense of the word. It touches user preferences with respect to size of the user network and characteristics of the technology, but also demographic characteristics of the users themselves. This also applies for infrastructure dependent technologies, but in addition to that, users only consider adoption of the technology as a sufficient amount infrastructure available. This is in line with the previous section, where we described that the diffusion of infrastructure (surfaced roads) tend to precede the diffusion of the technology (cars). Hence, users are expected to be heterogeneous with respect to infrastructure availability requirements. However, as all users require some infrastructure to be available we expect heterogeneity of users for infrastructure dependent technologies to be smaller than for regular technologies. Although, users are expected to be more like each other regarding infrastructure availability, heterogeneity of users will be crucial for the substitution process. For example, early adopters of new technologies are expected to be satisfied with limited infrastructure available while late adopters require complete infrastructure coverage. The diffusion of the technology, in a situation where all consumers are homogeneous and require similar availability of infrastructure, can only proceed when infrastructure availability is developed to a state where this requirement is fulfilled. So, heterogeneity of users is very important for a gradual substitution process and will not proceed when heterogeneity is to low. The more users differ in their requirement for infrastructure availability the faster technological substitution process will be.

Related to the heterogeneity of users is the question whether users of infrastructure dependent technologies experience local or global externalities. In section 2 is described that with global externalities one dominant technology is likely to emerge, which strengthens lock-in symptoms. The infrastructure required for a new technology is often a nation wide network and therefore characterized by global externalities, which suggest that substitution is unlikely to occur. However, in reality it appears that different subsystems that partly use the same infrastructure can survive next to each other. Although, the Gasoline subsystem is dominant, also Liquefied Petroleum Gas and Diesel have significant market shares. This suggest that users are influenced also by local externalities and have diverse preferences. Moreover, whether users in the transport sector experience local externalities or global externalities depend on their travel behaviour. For example, some users of the transport infrastructure travel the whole country (global network), while others only use infrastructure in their local environment. So, also regarding the kind of externalities users are heterogeneous. This heterogeneity might affect the substitution process of infrastructure dependent technologies. In the previous section we explained that such Large Technical Systems are expected to spread out from innovation centers to its hinterland as well as sub-innovation centers. Because infrastructure will only be available locally in these innovation centers, users that experience local externalities are important for the early stages of the substitution process. Therefore, we expect that the more users experience local externalities the faster the technological substitution process takes-off.

Technological substitution is also expected to be easier when the population size of the old system is small. However, as the words large technological system says, the installed based and network of the existing system is in most cases large. Hence, we expect a situation of a small initial population size is not valid for infrastructure dependent technologies.

Another mechanism to stimulate the early development of 'regular' technologies is the presence of experimental users, that do not care about the number of users of a technology or the inferior quality in the early stages of development. As long as technologies are independent from the availability of an infrastructure network it holds that experimental users might be a solution to escape the lock-in. However, for infrastructure dependent technologies the experimental users need some infrastructure to experiment with too. Hence, even to get some experimental usage infrastructure investments are required, meaning that experimental users are less likely to be present for LTS, at least not on an individual level. In the previous section we described that the growth phase starts with inventor-entrepreneurs who are involved in the diffusion of both the infrastructure and the technology. When experimental users are involved in both infrastructure and technology adoption it might stimulate the early development of a new system. Because the development of infrastructure dependent technologies often boils down to large scale projects, governments or big companies that develop their own internal infrastructure might act as experimental users/ early adopters. For example, the Dutch Airport Schiphol announced to experiment with electric cars to transport employees across the airport and installed their own charging facility on the airport. This makes it less likely that experimental users appear for new infrastructure dependent technologies than for 'regular' technologies. However, users that adopt both infrastructure and technology might act as experimental users and are expected to stimulate technological substitution.

A government that acts as experimental user or early adopter can be interpreted as a kind of self-fulfilling prophecy. If government prefers that the substitution of an infrastructure dependent technologies takes place, it has perfect foresight as it acts as experimental user on the one hand and subsidizes infrastructure and technology development on the one other hand. A situation in which other users also have perfect foresight would probably positively affect the substitution process, but is unrealistic. Although, some behaviour of the government seams to be based on perfect foresights, frequently it appears from government behaviour that governments had no foresight or was mistaken. For example, governments subsidize more than one competing technology at the same time (vehicles on hydrogen, natural gas or electricity) or the government stimulates technology A one year while it invests in B the year after.

Another difference with 'regular' technologies is that it is almost inevitable that governments contribute to the early competitiveness of LTS. Almost without exception are governments involved in the development of LTS, by giving subsidies to infrastructure suppliers and consumers. However some existing systems such as railroads in Britain were initially developed by private investors [18]. Early competitiveness of quality and price of the new technology with incumbent technology was found as requirement for a smooth substitution process in section 2. Regarding the early competitiveness of infrastructure dependent technologies upfront infrastructure availability for a new technology should be close to the infrastructure availability of the old technology. A significant difference of infrastructure availability in the early phase of the substitution process might hinder diffusion of the new technology. In addition, the costs of installing and using the infrastructure should not differ substantially from the costs for the old infrastructure. Users might abandon early adoption when differences in costs are too high. However, the previous section made clear that different LTS were introduced in the high ends of the market, which suggest that early competitiveness is not a requisite per se. Due to technological learning the technology also becomes attractive to low ends of the market in a later stage. Thus, also here heterogeneity of users appears to be important, different users adopt at different moments in time. Whether an LTS will be competitive in an early stage of development also depends on how close the new technology is a substitute to the old technology. A perfect substitute must be very competitive if users only look at prices, while for more differentiated technologies the focus is on the new characteristics that distinguishes the new from old technology and early competitiveness will therefore be of less importance. When technological substitution takes place with differentiated technologies this refers to technological succession. When technologies differ with regard to some characteristics, old systems not always disappear when a new system successfully enters the market. Users might keep both technologies for different purposes. For example, the electric car can be introduced as a substitute of our current ICE cars, but when it remains only suitable to travel short distances, it might be introduced as city car for the high end of the market in addition to the current ICE cars, that then remain attractive for the long distance. In this case users could adopt both technologies and substitution will not take place, although the new technology is successful. However, in all cases early competitiveness increases the probability of success for the new technology.

On the one hand early competitiveness could be within easy reach for backward compatible technologies and difficult for less compatible technologies, on the other hand compatible technologies are often a closer substitute, meaning that early competitiveness is important. The degree of compatibility of infrastructure dependent technologies is defined as: the fewer infrastructural adjustments are necessary, the more backward compatible an infrastructure dependent technology is with the current system [23]. Incompatible technologies might be perceived as more complex systems which, according to section 3, tend to diffuse more slowly. For example, the hybrid electric vehicle sold by Toyota since 1997 is completely compatible with the existing infrastructure and experiences therefore much less diffusion barriers than Fuel Cell vehicles that also require changes in infrastructural components [8]. Shy's model, discussed in section 2, which illustrates that the substitution process of backward compatible technologies tends to proceed faster. For infrastructure dependent technologies this might be the case because consumers are more used to current infrastructure, switching costs might be lower and the development of new infrastructure receives probably less resistance from all involved actors. For example, fuel suppliers might prefer the development of a Natural Gas transport system to an electric transport system, because refueling Natural Gas is quite similar to the current refueling system and keeps the business for suppliers as usual, while charging electric cars at home might cut benefits for fuel suppliers. So, the diffusion of backward compatible infrastructure dependent technologies tends to proceed faster and accelerates the substitution process.
However, there is also a counter effect that often is disregarded in this discussion. When technologies are backward compatible to a high extent, the decline of the old infrastructure might slow down because the infrastructure fits to both the old and new technology. The infrastructure for using the old technology remains intact, which decreases the incentives for users to switch to the new technology. When new infrastructure is necessary, late adopters might be forced to switch to the new systems as soon as the old infrastructure decays. Hence, backward compatible technologies might decelerate the substitution process, because it slows down the decline of the old technology. Compatibility of infrastructure is thus expected to stimulate early development of the new system, but might hinder complete substitution in later phases.
Whether the new technology is compatible or not also affects how users treat networks size and quality: as substitutes or complements. Network size can refer both to the network of users and the infrastructure network. The development of both networks is related, as we discussed in the previous section, but for this question we primarily focus on network of infrastructure. Although users are to some extent heterogeneous in how they treat network size and quality, we expect threating them as complements will dominate especially in the early phases of the substitution process. Users will have a threshold level of both quality and

network size in terms of infrastructure that is minimally required, which means that utility increases only if both network size and quality increases. In later phases, as plenty infrastructure is available treating them as substitutes might dominate, because users can gain more utility as only quality increases and users become indifferent when network size decreases slightly as long as quality increases. In case a technology is perfectly compatible with the current system no adjustments to infrastructure are necessary, which makes the substitution process in fact similar to the substitution process of a 'regular' technology. As the network size of infrastructure is not an issue anymore this might result in more users treating network size and quality as substitutes. Similar to 'regular' technologies the network of users is then affecting the utility function.
Summarizing, the substitution/succession/diffusion process of infrastructure dependent technologies differs from 'regular' technologies. The eight mechanism for overcoming lock-in, we found in models on technological substitution and succession discussed in section 2, are often expected to affect the substitution of infrastructure dependent technologies in the same direction, but on a much larger scale or in a more complicated way. However, in some cases the dependency of infrastructure might lead also to a counter effect. We also showed that the mechanism are not mutually exclusive, which makes unambiguous expectations impossible. For instance, the importance of early competitiveness depends on the degree of compatibility, which in turn affects whether heterogeneous agents treat network size and quality as substitutes or complements.

In the the next section we discuss how we want to test these expectations in the future.

5 Future work

The next step is to create a model that bridge between the micro mechanism found section 2 and the empirical macro patterns of the substitution of infrastructure dependent technologies described in section 3. Agent based models enable us to study how these macro patterns emerge from micro mechanism because it uses a bottom-up approach. We thereby consider the development of large technological systems from an evolutionary perspective and are interested in how the substitution dynamics emerge from the adoption decisions of consumers and the investment decisions of infrastructure builders. The behaviour of our model should give insights in the substitution dynamics and will be studied by simulations, which also enables the testing of our expectations. Agent based models allow simulations of decision making rules of various actors over a certain period of time in which the behaviour of all actors is continuously updated. Actors, based on their decision rules, select (different) components of (different) systems, which generates the competition and substitution dynamics between alternative systems we are looking for.

The model describes the competition between a new (more sustainable) and and existing technology infrastructure combination where the new technological system is a potential substitute for the existing technological system. The actors in the system evolution model are consumers and infrastructure builders. The number of systems evolving can be infinite, but here we consider the stylized case with two competing systems [1]. The system grows or becomes smaller through the investment decisions of system builders and the adoption decisions of consumers. System builders invest in infrastructure components, while consumers decide on the adoption of the technology components. Figure 1 includes all components and actors of the model and shows that consumers and system providers adopt different components of a system. The interaction processes between the diffusion of infrastructure and technology is represented by the dashed arrows. Consumers are influenced in their decision making by the availability of infrastructure. And, similarly, the adoption of technology by consumers affects the investment decision of system builders.

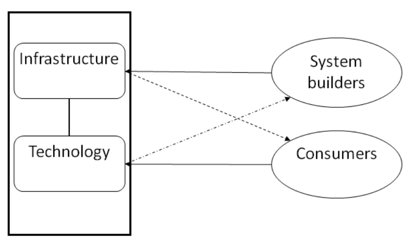

Figure 1: Model components: Infrastructure, technology, consumers, system builders, and the interactions between them

The results of our simulation model enables us to contribute to the dominant design literature, how the substitution process of infrastructure dependent technologies differ from 'regular' technologies. These insight might help actors involved in the development of a new and sustainable Large Technological System.

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