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Interfaces with Other Disciplines

Adoption of an emerging infrastructure with uncertain technological learning and spatial reconfiguration

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ABSTRACT

This paper develops a stylized (or conceptual) system optimization model to analyze the adoption of an emerging infrastructure associated with uncertain technological learning and spatial reconfigurations. The model first assumes that the emerging infrastructure will be implemented for the entire system when it is adopted. With the model, this paper explores (1) how the emerging infrastructure's initial investment cost, technological learning and its uncertainty, market size, and efficiency influence the adoption of the emerging infrastructure and (2) how the efficiency and investment cost of the associated technology (which will be located in a different place with the adoption of the emerging infrastructure) influence the adoption of the emerging infrastructure. Then, this paper extends the model and explores whether it is a better solution to implement the emerging infrastructure for part of the distance from resource site to demand site if its efficiency is a function of the implemented distance. With optimizations under three types of efficiency dynamics, this paper finds that whether the emerging infrastructure should be implemented partly or entirely is not determined by the value of its efficiency but by the dynamics of its efficiency.

1. Introduction

Models of technology adoption can be grouped into one of two streams. The first stream addresses the psychology-based acceptance of new technologies by individual users or organizations. Well-known models in this stream include the technology adoption lifecycle model (see Rogers, 1962), the Bass diffusion model (Bass, 1969), and the technology acceptance model (TAM) (see Bagozzi, Davis, & Warshaw, 1992; Davis, 1989). The second stream analyzes technology adoption from the perspective of social planning instead of from the perspective of individual users or organizational psychology. Well-known examples of such models include the MESSAGE (Messner & Strubegger, 1994) and MARKAL (Seebregts, 2001) models. Technology adoption with social planning is not commonly appropriate for end-use technologies; instead, they are more applicable to upstream technologies, e.g., power plants.

Both of these streams have paid little attention to the adoption of new infrastructure technologies. Although most models in the second stream include infrastructures as part of a techno-economic system, infrastructures are commonly treated as links among different technologies or activities, rarely as main objects under study, and so, little work has been done to analyze how technological learning and its uncertainty influence the adoption of an emerging infrastructure.

Establishing an emerging and advanced infrastructure commonly requires very high initial investment cost. For example, establishing a railway for maglev trains needs a huge investment, much higher than building a regular railway. Technological learning, which means the cost of using new technologies tends to decrease as the experience of using the new technology accumulates (Arrow, 1962; Arthur, 1989), is thought of as an endogenous driving force for the adoption of currently more expensive new technologies (e.g., Ma, Grubler, & Nakamori, 2009; Schwoon, 2008). Technological learning has been missing from most of the traditional models in which technological change has been largely treated as exogenous (see Ma, Grubler, & Nakamori, 2009). With technological learning, the cost of an emerging infrastructure could decrease in the future. However, it is not a free lunch. Cost reduction in the future relies on investment in the early stages of infrastructure development. Historical observations have shown that technological learning is quite uncertain (McDonald & Schrattenholzer, 2001). When a new advanced infrastructure technology emerges, from a social planner's perspective, when and at what pace should it be implemented to replace the existing one, especially when the future of the emerging technology is still uncertain? For example, when should human society widely establish the infrastructure for maglev trains? The problem could become more complex

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when the adoption of an emerging infrastructure is associated with the relocation of other important elements of the techno-economic system.

Adoption of an emerging infrastructure technology can enable (or is accompanied with) the re-optimization of the topology or spatial layout of a techno-economic system. From a perspective of system optimization, when adopting an emerging infrastructure, social planners need to consider the cost of relocating elements associated with an infrastructure. For example, for a coal-electricity system, if the coal resource is far away from the demand site of electricity,[1] the traditional solution is to transport coal by railway and trucks from resource cites to demand cites where coal power plants are established (see Ma & Chi, 2012). A UHV (Ultra High Voltage) grid is believed to be able to transmit electricity for a long-distance efficiently, and thus coal power plants can be moved from demand sites to resource sites. When adopting a UHV grid, social planners need to consider the cost of moving coal power plants as well as the cost of establishing a UHV grid with uncertain technological learning. Another example could be cloud computing. Cloud computing enables us to move the computation capacity from the end-use site to the cloud. It can save the cost of the end-use site, but it will require powerful host computers as well as a more powerful infrastructure for transmitting data, which is costly (see Buyya, Yeo, Venugopal, Broberg, & Brandicc, 2009).

In addition to issues about when and at what pace to establish an emerging infrastructure with uncertain technological learning and the relocation of other elements associated with the infrastructure, another issue is what will be the appropriate length of implementing the emerging infrastructure if its efficiency is a function of its implemented length. For example, when establishing a UHV grid, should it be implemented over the whole distance from resource site to demand site or just part of the distance, and if the better solution is to implement it for part of the distance, then what should the length of the part be?

In short, this paper explores the above issues by developing a stylized (or conceptual) system optimization model with uncertain technological learning. The stylized model contains two types of infrastructures (an existing one and an emerging one) and a product producing technology that can be located at different place with different infrastructure. Diffusion of new technologies, especially a new infrastructure, commonly takes a long time (e.g., see Grubler, 2004). Therefore, the model introduced in this paper is built from a long-term perspective. The model first assumes that the emerging infrastructure will be implemented for the entire system when it is adopted. With the model, this paper explores (1) how the emerging infrastructure's initial investment cost, technological learning and its uncertainty, market size, and efficiency influence the adoption of the emerging infrastructure, and (2) how the efficiency and investment cost of the associated technology (which will be located in a different place with the adoption of the emerging infrastructure) influences the adoption of the emerging infrastructure. Then, this paper extends the model and explores whether it is a better solution to implement the emerging infrastructure for part of the distance from resource site to demand site if its efficiency is a function of its implemented distance.

The model and study presented in this paper do not aim to represent the reality in terms of technological or economic details; instead, it is mainly for heuristic purposes.

The rest of the paper is organized as follows. Section 2 describes the stylized techno-economic system of the optimization model. Section 3 presents the optimization model and analyzes (1) how a new infrastructure's initial investment cost, technological learning and its uncertainties, efficiency, and demand influence the decision of adopting it; and (2) how the efficiency and investment cost of the associated technology influences the adoption of the emerging infrastructure. Section 4 further extends the model and explores whether it is a better solution to implement a new infrastructure partly if its efficiency is a function of its implemented distance. Section 5 gives concluding remarks and suggestions for future work.

[1] As in the case of China, the largest consumer of coal in the world.

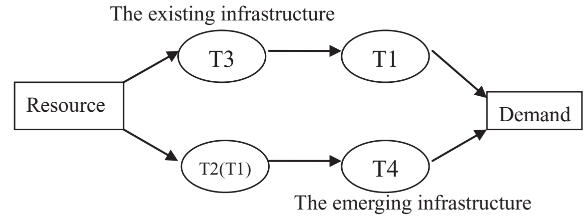

Fig. 1. An illustration of the stylized model.

2. A stylized techno-economic system

For the sake of transparency, the techno-economic system of our model is quite simple and stylized. The simplification also follows previous research on endogenous technological change models (e.g., see Chi, Ma, & Zhu, 2012; Grubler & Gritevskyi, 1998; Ma and Nakamori, 2009; Manne & Barreto, 2002). In the system, the economy demands one homogenous good/service (e.g., electricity), and the demand increases exogenously with an annual growth rate. There is one resource for producing the goods (e.g., coal), and its extraction cost increases with resource depletion. There is one technology to produce the goods from the resource (e.g., coal power plant). There are two types of infrastructure technologies, an existing one and an emerging one. The existing infrastructure (e.g., railways) is used for transporting resource, while the emerging one (e.g., ultra high voltage grid) can be used to transport the goods. Thus with the existing infrastructure, the plant that produces the goods should be located at the demand site, and with the emerging infrastructure, the plant can be located at (or close to) the resource site. Although applying the emerging infrastructure is believed to be able to improve the entire system's efficiency as well as being more environmentally friendly, currently it is much more expensive than the existing one in terms of investment cost. The emerging infrastructure has technological learning potential, which means its investment cost will decrease as experience with it increases, but the learning remains uncertain.

We use T1 and T2 to denote plants that produce the technology at the demand site and at (or close to) the resource site, respectively. In other words, T1 and T2 are the same technology applied at different sites. We use T3 and T4 to denote the existing infrastructure and the emerging infrastructure technology, respectively. When adopting T4, in addition to using it to substitute T3 for all of the distances from resource site to demand site (see Fig. 1), an alternative way is to implement it for part of the distance (see Fig. 8), which means T2 will be located between the resource site and the demand site, the old infrastructure will be used to transport resource from resource site to the location of T2, and goods will be delivered to the demand site from the location of T2 by T4. In this case, during the process of adopting T4, the existing infrastructure will exist in the system with two statuses. One is from resource site to the demand site, which is denoted with T3, and the other is from resource site to the location of T2, which will be denoted with T5. In other words, T3 and T5 are the same technology implemented with different lengths.

In the following discussion, we assume the product for the end-use is electricity. This assumption does not lose the generality of the model. Readers can also assume the product is computation service or other products/service that can be produced at different sites with different infrastructure. The purpose of assuming the product is electricity is just to give a vivid background for the model so readers can imagine the story of the model more easily. With this assumption, we can imagine the resource is coal, T1 and T2 are coal power plants, T3 is