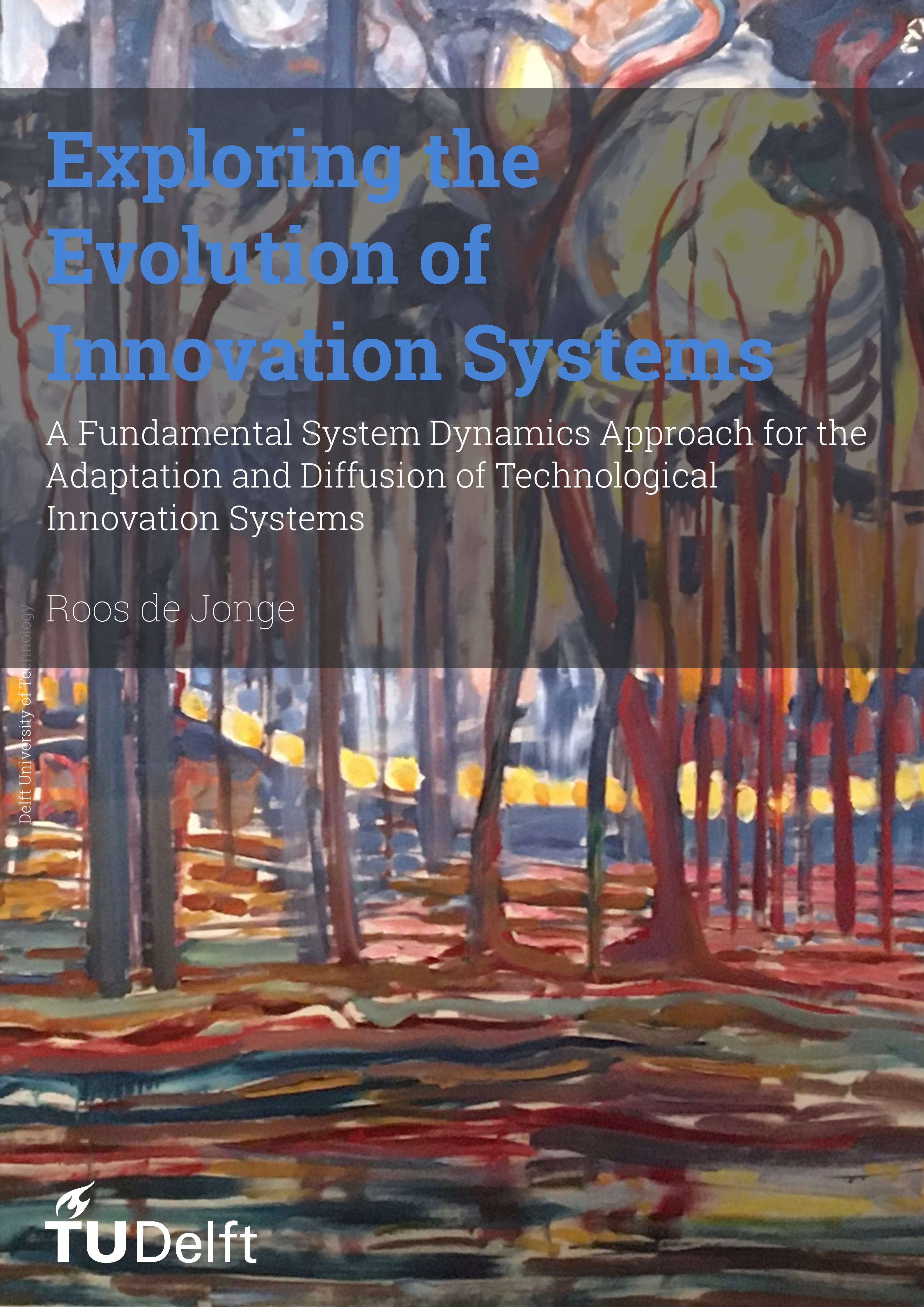

Exploring the Evolution of Innovation Systems

A Fundamental System Dynamics Approach for the Adaptation and Diffusion of Technological Innovation Systems

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by

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Executive Summary

This study takes initial steps to understand why 47% of companies creating Radically New Technological Innovations fail before reaching large scale diffusion and how to prevent such failures. This was achieved by integrating Ortt's (2010) evolution model—which states that an innovation passes through a development and adaptation phase before reaching large-scale diffusion—with the Technological Innovation System framework, which emphasizes that an innovation encompasses more than just its technical features. These combined theories were then analyzed using the System Dynamics Modelling approach. The main question in this process was: "How can we develop a System Dynamics Model that accurately portrays the interactions among elements within the Technical Innovation System, shedding light on the system's behavior across different phases and identifying factors hindering the progression of the adaptation into the diffusion phase?"

To answer this question, we developed a method, a model depicting the interactions between the TIS-factors, a theory on transitions between phases, and a simulation model demonstrating the influence of certain factors on these transitions.

The developed method is based on synthesis, in which theories on the factors within the TIS, namely customers, price, performance, production, networks, institutions, and complementary products and services, are combined into one coherent framework. This framework acts as a hypothesis, outlining the variables that make up the factors and defining their interrelations. From this hypothesis, a conceptual and a simulation model can be built which can be validated using expert interviews and experimentation.

Using this method, we built a conceptual model that maps the variables and their relationships, while also clearly stating its assumptions. Through evaluating this model, we identified customers, production, networks, and complementary products and services as potential drivers in the system. Additionally, we found that growth in legitimacy and R&D can have both positive and negative influences on the system, depending on how other factors develop.

To understand how the TIS is first adapted and then reaches large scale diffusion, a theory on market transitions was designed. Here we hypothesized that the adaptation and diffusion phases are really a series of heterogeneous markets that are characterized by different demand preferences. Initially, during the adaptation phase, these are niche markets, while in the diffusion phase, the innovation can enter larger and more demanding main markets. Additionally, we proposed three pathways for an innovation to transition from one market to another: first, by evolving its TIS to align with the market's demand preferences, which is often essential in main markets; second, when demand preferences shift to match with the TIS, typically seen in smaller niche markets; and third, when both demand and the TIS evolve to better align.

Lastly, our goal was to begin to identify which elements are crucial in market transitions. To achieve this, we constructed a simulation model that illustrated the interaction between standardization and potential shifts in demand preferences. The variable *Standardization* is grounded in the assumption derived from the conceptual model that, given enough time, all TISs will produce a standardized product. Our

findings indicate that when entering a market, having a high level of standardization is essential to achieve high-level diffusion, particularly in markets focused on a developed TIS. Conversely, to prevent low diffusion levels, it is important to enter the market only when the product is favored by consumers, especially in markets determined by external demand preferences; additionally, low standardization should also be avoided.

In conclusion, the synthesis method created here can be used to indicate what elements are essential in enabling or hindering the progression from the adaptation to the diffusion phase. Initial conclusions indicate that there are several drivers and potential hindrances within the system and that both standardization and shifting demand preferences can greatly impact possible transitions, depending on the specific characteristics of the market.

As these are the first steps in a long line of research, there is so much more to be done. For this it might seem obvious to only look to the future and aim to design more specialized conceptual models, or a simulation model that encompasses all elements. However, I also want to invite you to look to the past and see how this study can be used to clarify the theories and methods that form its foundation.

Contents

1 Introduction

Innovations have been pivotal in shaping modern societies and addressing global challenges. New technologies like photovoltaic cells and electric vehicles have significantly influenced both the fight against climate change and the way we design our environment (Dewald & Truffer, 2011). However, before these innovations can have such an impact on society, they must be developed and introduced to the market. This process is fraught with challenges, and many innovations either fail to reach the market or are killed quickly once they do (Ortt et al., 2007). This tendency for failure is a point of concern for two sectors: the market and the government. For companies, innovations represent a substantial risk, as technological changes can disrupt entire markets and determine the fate of businesses (Sood & Tellis, 2005). For governments, the success of innovations can drive significant policy shifts, whether in pursuing goals like advancing the energy transition or ensuring citizen safety with technologies such as self-driving vehicles. In summary, gaining a deeper understanding of the system that leads to the failure or success of innovations is crucial for both companies and governments. This knowledge enables them to devise more effective strategies for developing innovations and market strategies, and for crafting appropriate policies.

Both markets and governments face particular uncertainty regarding one subset of innovations: Radically New Technological Innovations (RNTIs). These innovations are deemed radical either due to their substantially improved price/performance ratio compared to existing technologies or because they introduce new functionalities. It is because of these increased ratios and new functionalities that these innovations have the potential to offer breakthroughs in the energy transition (Jacobsson & Bergek, 2011). However, due to their radical nature they also tend to face heightened market risks in comparison to existing technologies (Min et al., 2006). This results in the failure of 47% the companies who pioneer these RNTIs (Ortt, 2010). Notable barriers for success are the lack of legitimacy of the technology, the absence of complementary products and services, and the want of a network that can supply these products and services. This implies that, even if a product is technologically superior to its competitors, it might not be commercially superior (Olleros, 1986). As a result of these specific obstacles, it often takes a long time before these innovations start to diffuse, thereby increasing the risk of failure (Ortt & Kamp, 2022). This presents an intriguing conundrum: on one hand, innovations are so influential that they significantly shape our policies and can make or break companies. On the other hand, their success is highly uncertain. In short, we rely heavily on innovations, yet their success or failure often appears beyond our control.

1.1. The Lifecycle of Innovations

One way to work towards a solution for this problem is by better understanding the system in which it occurs. If we understand why it takes such a long time for a RNTI to diffuse, we could develop the tools to shorten this timeframe. Extensive research has already been done on this subject, which has significantly altered how researchers view the diffusion of innovations.

Traditionally, when researchers consider interactions between markets and innovations, they presume a pattern of development and diffusion. They assume that the innovation is first developed, after which it enters the market. There it is either adopted or rejected based on how well it can compete with other technologies. If it is accepted, it will automatically become the dominant technology on the market (Ortt, 2010). This pattern is known as the S-curve, see Figure 3.1.

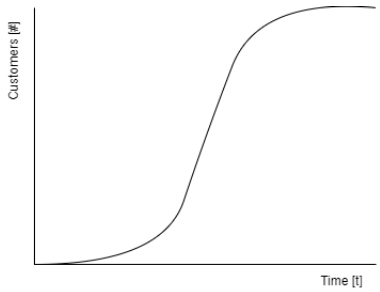

Figure 1.1: S-curve based on Rogers (1962)

More recently, researchers have started to question this abrupt change from development to diffusion. Through studying the lifecycle of innovations, they have discovered that, nestled between the development and diffusion of an innovation, there is a third stage: the adaptation phase (Ortt, 2010).

When an innovation is first developed it is often not ready to compete on the mass market, due to, e.g., their relatively high price or low performance. The innovation can then disappear from the market all together. Alternatively, it can also find its way into a niche market. This market differs from the main market, because its customers apply a different set of requirements to the innovation. They might accept a higher price or lower performance (Geels, 2010). This phenomenon can be found in a range of innovations, but is also prominent in the sale of electric vehicles by Tesla. Initially, the company's vehicles commanded high prices, which were justified by the novelty and luxury they offered, attracting early adopters despite the steep costs. The income the sales in this niche market granted, afforded Tesla the opportunity to invest in the production and performance of the vehicles. As a result, they started to produce better and cheaper cars that could begin to compete in other markets (Shao et al., 2021).

If Tesla had been forced to enter the main market from the start, it would most likely have failed. However, by appealing to niche markets, it was able to adapt gradually to the market and survive. This, and many other innovations, show the existence of an extra phase in the innovation-lifecycle, in which the innovation gradually adapts to the system: the adaptation phase. This leads to a new pattern, which is modeled in Figure 1.2.

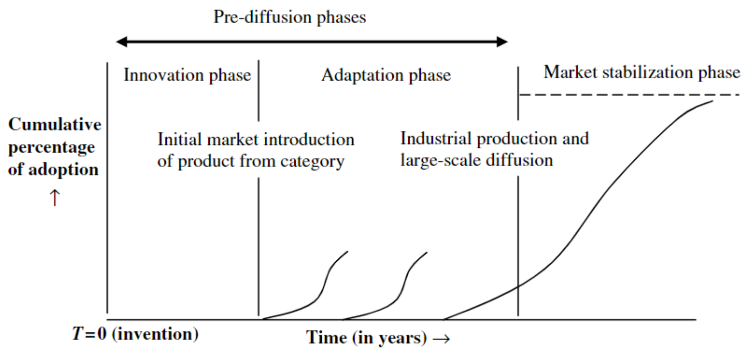

Figure 1.2: Evolution model from Ortt (2010)

In short, recent research shows that an innovation is not presented to a market in its final form for immediate adoption or rejection. Instead, it gradually adapts to the market throughout its lifecycle to ensure survival.

Understanding the existence of the adaptation phase in the innovation system is not only crucial for gaining insights into how the system operates, but it also carries significant economic ramifications. Prior to introducing an innovation, companies must formulate a market strategy, which is heavily influenced by the anticipated market characteristics. For instance, if a producer intends to target a niche market, they will invest in small-scale production facilities to customize products according to customer specifications. Conversely, opting for a mass market strategy involves investment in large-scale production to meet high demand. Therefore, selecting a market entails substantial investment and commits a company to production methods that are difficult to alter (Ortt et al., 2007). Recognizing the potential to enter not only mainstream markets, but also niche markets, is thus of paramount importance and should not be underestimated.

1.2. Technological Innovation Systems

However, the addition of the adaptation phase is not the only change of note that has occurred in recent years. Researchers have also begun to examine markets themselves more critically, delving into their composition and structure. Customarily, markets were perceived as spaces where customers assessed products based on performance and price, selecting the one that best suited their criteria (Geels, 2010). This is a very clear, but also very limited perception of markets. Factors beyond price and performance can also influence the decision-making process. E.g., one of the main reasons that Tesla became affordable for a bigger group of customers in Europe was because these customers could apply for subsidies (Shao et al., 2021). This shows that institutions also play a role in the adoption of innovations.

This realization has led to the development of a new framework: the Technological Innovation System, or TIS. A TIS consists of all the actors and factors around an innovation, which are often summarized as networks and institutions (Dewald & Truffer, 2011; Ortt & Kamp, 2022). The idea behind the TIS is that by understanding these factors, we can learn how the innovation system around a particular technology functions (Bergek et al., 2015). To further this understanding, Ortt & Kamp (2022) have compiled a comprehensive list of all the factors that are of importance in the TIS. Their list consists of seven elements and reads as follows;

1. Product performance and quality; whether the artifact is regarded as a viable option by potential consumers.
2. Product price; the cost for acquiring and using the product.
3. Production system; the existence of a production system that can deliver high-quality products in large quantities.
4. Complementary products and services; the products and services an artifact needs to be produced, distributed, used, maintained and be disposed of.
5. Network formation and coordination; the network of actors that acquire the resources needed to launch and improve the product.
6. Customers; the potential buyers and their requirements.
7. Innovation-specific institutions; institutions such as policy and regulations can both support and block the development and diffusion of the product.

The keen reader will observe that the artifact as such is not a part of the framework. Instead, it is measured in its qualities; its price, performance, production and its complementary products and services. On top of that, this framework also highlights the role of factors that are not traditionally associated with the artifact itself: the customers, networks, and institutions. When analyzing the relationships between the elements within the TIS one could argue that it consists of three groups; the technology, the actors and the institutions. These groups do not stand alone within the TIS, but they influence each other. Performance, for example, can be influenced both by governmental regulations and by quality standards set by a sector. An overview of the boundary of the system and its factors, divided by group, is given in Figure 1.3.

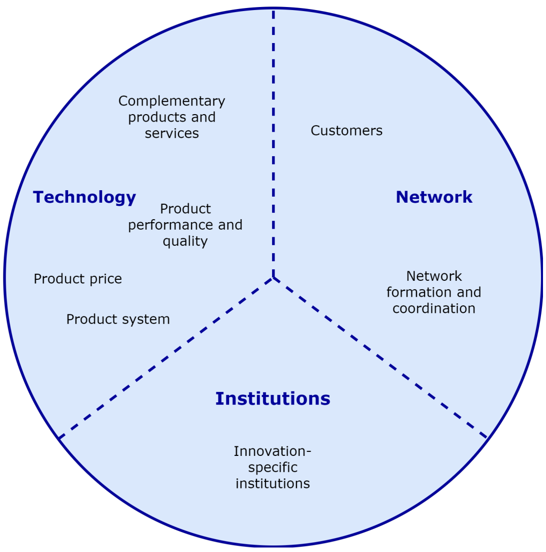

Figure 1.3: The elements in the TIS, based on Ortt & Kamp (2022)

Over the last 20 years great steps have been taken to improve our understanding of the systems in which innovations develop, are adapted, and diffuse. While this has influenced the way policy around innovations is made, it has not prevented us from losing RNTIs. I hypothesize that this is the case, because the current understanding of innovation systems misses one crucial element; the dynamic nature of the innovations and the systems in which they exist.

1.3. A Dynamic System

Currently, the TIS is conceptualized as a collection of elements. It states that before an innovation can diffuse, it has to meet a set of standards; it has to have the right price, a big enough network, etc. Once the TIS has all those things, the innovation will automatically enter the diffusion phase and become successful. In reality, the system is far more complex, primarily because it operates as a dynamic system. This changes our perception of the system in three ways.

Firstly, Figure 1.2, which shows the phases of diffusion, displays separate diffusion lines that stop mid-air and start again from zero. This implies that the diffusion within a market occurs as a discontinuous process, wherein customers are counted separately within each market, leading to a reset of customer count to zero once the market saturates. However, in reality, we do not analyze individual markets separately; instead, we examine the percentage of all customers adopting a particular innovation. As a result, rather than visualizing the process as discontinuous, as in Figure 1.2, it should be depicted as continuous, as shown in Figure 1.4.

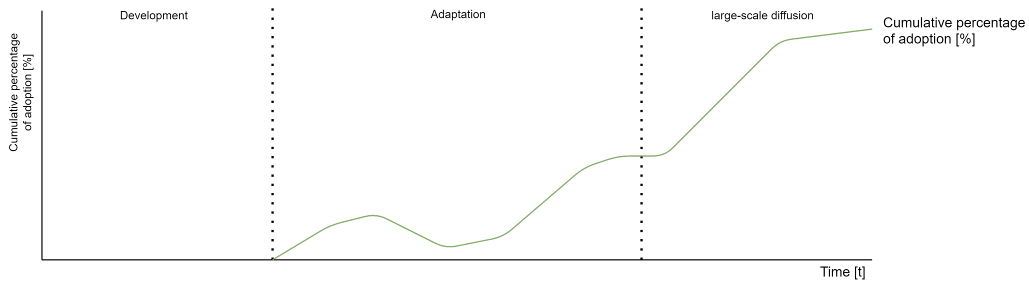

Figure 1.4: A change in customers based on Milling & Maier (2020)

Secondly, as implied in §1.2, the various elements are interconnected; they influence each other. They change each other's behavior. A strong network will, for example, be able to influence governments, thus creating institutions (Binz et al., 2016). Additionally, a higher expected price will lower the risk of investment, thus increasing the amount of money available for R&D, which in the end enhances the performance of the artifact (Milling & Maier, 2020). In Figure 1.5, there is an evident interaction depicted between *Price* and *Number of customers*. It is observed that as the price decreases, there is a corresponding increase in the number of customers at various points in the figure. This illustrates a commonly recognized mutual influence that exists between price and the number of customers.

At the same time, Figure 1.5 shows that this interaction between *Price* and *Number of customers* does not follow the same pattern throughout innovation diffusion. Milling & Maier's (2006) research indicates that the impact of price on the number of customers is considerably lower during the initial introduction of an innovation compared to when a company endeavors to saturate the primary market. At the first stage of the adaptation phase, as with Tesla, the customers are far more interested in the novel applications of the product than the price, but as the novelty wears off the price becomes more important. Also, when an innovation enters a new market and begins adapting to it, this process demands investment in areas like production, temporarily driving up the price. Hence, the behavior of the elements is dependent on the particular phase of innovation diffusion.

Ergo, we can conclude that the TIS is a dynamic system. This implies three things. Firstly, it is probably too elementary to visualize the adaptation of innovations as several lines that stop midair, as visualized in Figure 1.2, instead the cumulative elements have to be depicted as a continuous line. Secondly, the elements are not standalones, but they influence each other. Thirdly, the behavior of the system varies depending on the stage of diffusion in which the innovation is situated. This means that the behavior of the TIS cannot be fully explained by Figure 1.2. Instead, the behavior of the system will most likely be more akin to the graph shown in Figure 1.5.

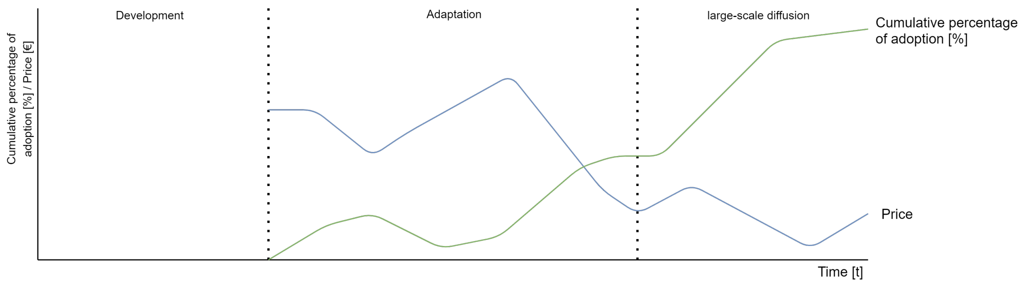

Figure 1.5: A dynamic model based on Milling & Maier (2020)

So, if the goal is to understand the innovation system, it is worth treating it as a dynamic system in our research in the hopes that it will broaden our perception of the TIS from only its elements to the relationships between them. Moreover, understanding these dynamics holds economic implications for companies engaged in developing and marketing these innovations. Discerning which interactions correspond to specific phases enables companies to make more informed decisions regarding market strategy, such as choosing between niche specialization and large-scale production. As described above, this knowledge lowers their investment risk, thus making the innovation a more viable option.

1.4. System Dynamics Modeling

We have concluded that there are three reasons to assume that the system is dynamic; it is continuous, its components interact, and it displays nonlinear behavior. The goal of this study is to gain a deeper understanding of this dynamic behavior, and to do so, we need an appropriate method. System Dynamics (SD) is particularly well-suited to these aspects of dynamism.

SD has a very particular way of looking at systems. It aims to describe all the elements within the system and their interactions. Or, as Davis et al. **(**Davis2007DEVELOPINGMETHODS) state it, it focuses on "how causal relationships among constructs [elements] can influence the behavior of the system". It also describes this behavior in a continuous way over a longer time period. However, what is maybe the most remarkable thing about this method is that it is based on the paradigm that there are feedback loops in the system that can cause it to behave dramatically differently from one moment to the next. It does this by taking behavior into account that is normally in the background of the system, but that can become very influential very suddenly. It is these kinds of behaviors that can cause disruptions like phase changes (Nava Guerrero et al., 2016).

To describe this dynamic behavior, SD makes use of four concepts. The first concept is feedback. This occurs when there is two-way causality; a variable influences another variable and vice versa (Auping et al., 2023). This feedback also exists indirectly. A higher production volume, for example, will lower the cost per unit, thus increasing demand and ultimately production (Milling & Maier, 2020). A feedback loop can be reinforcing or balancing. A reinforcing feedback loop will either continuously increase or decrease certain behavior, whereas a balancing feedback loop stabilizes behavior. Another concept in SD is time delays. In systems, there is often a delay between the moment of action and its effect. For example, it can take time before a production plant has been built, or a patent has been granted. SD incorporates these time delays and shows where processes can be improved. Previous research shows that time or lack thereof often determines whether an innovation will reach the large-scale diffusion phase, but it is not included as a proper factor in the framework (Ortt & Kamp, 2022). SD would make it possible to study time in innovation processes as a separate entity. The last concept is the stocks and flows. A stock is a parameter that displays the accumulation of a certain variable at a certain time. Customers could for example be divided into two stocks; those who have and those who have not acquired the artifact. A stock can be filled up or emptied by a flow (Auping et al., 2023). This indicates that as a potential customer transitions into a buyer, they will move from one stock to another, through a flow.

1.5. System Dynamics Modeling of Innovation Systems

There are instances where this systemic approach has already been utilized in analyzing the TIS. Uriona and Grobbelaar (2019) conducted a literature review in which they categorized the existing papers on System Dynamic Models (SDMs) of innovation systems. They found that they could divide the models into four categories;

1. R&D-dynamics: The maturation of the artifact in the development phase.
2. Innovation diffusion policies: The behavior of the system in the large-scale diffusion phase.
3. Science and technology policies: Policies are tested for a specific case.
4. Agglomeration policies: Clustering products and services in one geographical area.

All these models either depict specific instances or highlight a stage in the evolution of the innovation system, and they are all aimed at implementing policies. However, to grasp the essence of the TIS, we must delve into the core of the system. We must understand how the system functions as a cohesive entity, where all three phases play a role. Understanding how the elements identified by Ortt and Kamp (2022) are interconnected is crucial. Only by comprehending the joint behavior of all elements across all phases can we gain insights into the behaviors that contribute to the failure of RNTIs. This understanding, in turn, will hopefully give us the knowledge necessary to prevent the failure of these innovations.

In short, the aim of this study is to address a grand challenge, the diffusion of RNTI's, in which multiple perspectives play a role, including those of policymakers and companies, using a System Dynamics approach.

1.6. Research Questions

This leads us to the question of how to achieve this aim. Ultimately, we will need to create an SDM that combines both the elements from TIS literature and the phase changes from Innovation Management literature. More precisely, it should demonstrate how the system behaves in the various phases and identify which elements or interactions hinder the innovation from progressing into the diffusion phase. This objective can be formulated as the following research question.

> How can we develop a System Dynamics Model (SDM) that accurately portrays the interactions among elements within the Technological Innovation System (TIS), shedding light on the system's behavior across different phases and identifying factors hindering the progression of the adaptation into the diffusion phase?

To address this question, several steps must be taken. The first step involves designing a research methodology. This methodology will need to integrate insights from innovation management, which typically adopts an empirical focus, and SD, which examines system behavior. This leads to the following sub-question.

1. How can the existing information on the TIS be analyzed in such a way that it unveils the dynamic behavior of the system?

When we understand how to interpret the information, we can begin searching for the system's behavior. This information can be divided into three parts. These parts are arranged in a top-down manner. We will first search for the behavior of the entire TIS and only if we cannot find this behavior, we will look in more detail at the individual elements. This is to prevent us from getting lost in the details and loosing sight of the research goal.

The first part is as follows; how does the system typically behave over time? It could be an oscillating system where the number of customers continuously fluctuates. It could also be a system in which diffusion in different markets follows each other, as depicted in Figure 1.2. It could also be a combination of both. We will measure the overall behavior of the system in the number of customers. This leaves us with the second sub-question.

2. How does the number of customers in the TIS change over time?

The second part relates to the elements that make up the TIS. To understand the system on an aggregated level, we need to comprehend the interactions that constitute this aggregated behavior. To do so, we must know what the elements within the TIS consist of. In short, we need to grasp the theory behind these elements. As this research aims at composing a System Dynamics Model, we must define the elements as variables that can be measured and thus placed within a model. Due to time constraints, we will work under the assumption that the framework of building blocks as proposed by Ortt & Kamp (2022) encompasses all the elements within the TIS.[1]

3. How can the elements in the TIS as summarized by Ortt & Kamp (2022) be defined as quantifiable variables?

In the third part, we will look for the behavior of these elements and their interactions.

4. What behavior do the individual elements display, and how does this behavior influence the behavior of the other elements in the TIS?

The final part in addressing the main question is to identify the behavior that keeps the innovation from transitioning into the diffusion phase. This will be done by experimenting on the model that contains the aggregated behavior of the elements of the TIS. By omitting or adding variables and links, we will try to simulate the behavior that either prevents or causes the transition into the diffusion phase. To accomplish this, we will ask the last sub-question.

5. Which elements or interactions between elements within the TIS dictate whether an innovation progresses to the diffusion phase?

In short, we aim to answer five questions on three different levels. The first question searches for a research method. The second and final questions assess the behavior of the TIS in its entirety, while

[1] As a result, all other possible aspects of TISs will not be integrated in the model. This also includes the *influencing factors* as named by Ortt & Kamp (2022) which most notably contains competition between different technologies.

the third and fourth questions examine the elements and their behavior within the system, providing insights into the system's overall level.

By addressing these questions, we aim to develop an understanding of the dynamics of the TIS as a whole. The results will serve as an initial step towards shaping strategies and policies that can aid the survival of RNTIs in the market.

In Chapter 2, the method is developed, addressing the second sub-question. Chapter 3 introduces a conceptual model of the TIS, tackling the third and fourth sub-questions. In Chapter 4, this model is connected to the phase changes, answering sub-question five. Chapter 5 presents a simulation model to address sub-question two. The research concludes with a final conclusion in Chapter 6 and a discussion in Chapter 7.

2

Research Design

As stated in Chapter 1 Introduction, the aim of this study is to understand what behavior in a Technological Innovation System (TIS) determines whether an innovation reaches the diffusion phase. To research this, a System Dynamics Model (SDM) needs to be constructed that displays the dynamic behavior of the elements within the TIS. To do so, we need to look at Technological Innovation Systems from the viewpoint of a SD-modeller. We need to combine the knowledge gained by studying TIS, with the analytic research methods used in SD. Before we can start the research, we need to construct this new method. Therefore, the following question was asked, which will be answered in this chapter on research design.

> How can the existing information on the TIS be analyzed in such a way that it unveils the dynamic behavior of the system?

2.1. Methods in Innovation Management and System Dynamics

The research available on Technological Innovation Systems mostly consists of case studies and empirical data. An example is the development of the market for video games in Germany or the legitimization of potable water reuse in Southern California (Binz & Gong, 2022; Binz et al., 2016). On their own, these studies provide limited information on the innovation systems they research. The findings commonly relate to the particular region, and the research often focuses on a specific subset of elements within the TIS. In addition to that, all these case studies use their own definition of these elements, and they form their own theories on how these elements interact with their environment. A network can, for example, be defined as the number of actors in a group, but also as the amount of resources that the actors jointly possess. This definition informs a theory on how the network influences the broader system. Does it matter how many actors join a network, or what they bring to the table (Musiolik et al., 2012)?

To analyze the behavior of the TIS, we need to create a method that can systematically organize the existing literature into coherent theories. This method should be able to perform the following steps, as illustrated in Figure 2.1. First, it must be capable of generating a consistent definition for each element. Second, it should use the literature to describe the relationships between the elements. Finally, it should combine these theories into a system dynamics model.[1]

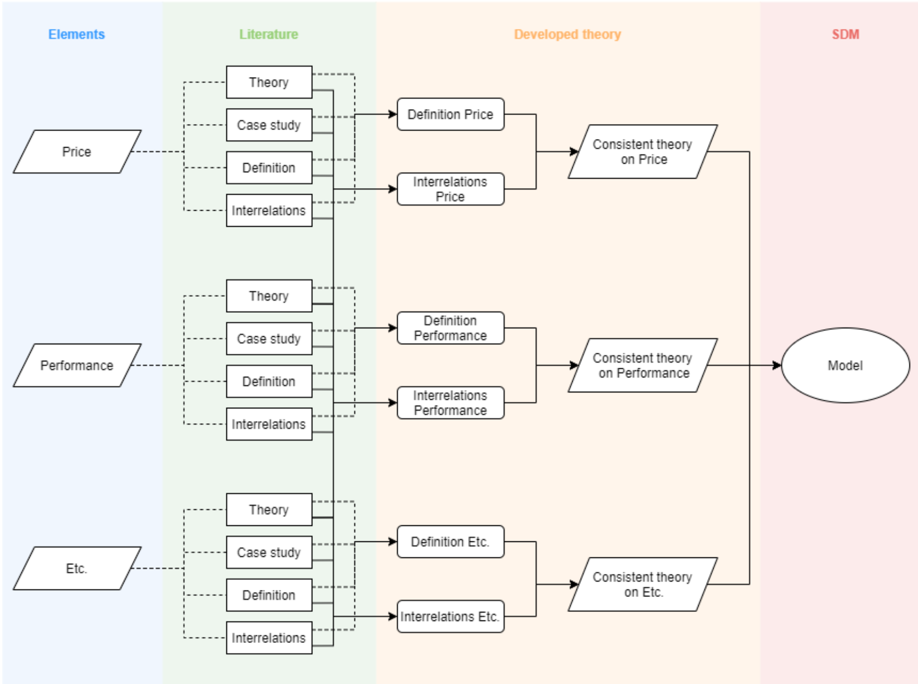

Figure 2.1: A first conceptualization of the method

The method we can follow to construct this theory has to help us find the contradictions between the theories, e.g., in how they define the elements, and harmonize them. It operates on the premise that it is feasible to achieve coherence among these elements. Consequently, it suggests that every individual TIS represents a specific variation of a universal behavior that is consistent across all TISs. Thus, when examining different TISs, we anticipate encountering a fundamental behavior underlying these systems that remains stable across all instances. This assumption—that systems exhibit universal behavior—coincidentally aligns with the paradigm on which System Dynamics is built (Nava Guerrero et al., 2016). Consequently, we will begin our investigation to find a suitable method there.

There are certain known methods in SD that can be employed to find this fundamental behavior: grounded theory and hermeneutics. Grounded theory serves the purpose of identifying themes, concepts, and, in this context, behavioral patterns within textual data. These identified concepts and patterns have the potential to be translated into variables, feedback loops, time delays, as well as stocks and flows within the model. The process of discovering these concepts and patterns involves taking notes (or memoing) while examining the texts. These notes are then used to search for overarching themes or behaviors (Auping et al., 2023; Luna-Reyes & Andersen, 2003). However, there is a good reason for dismissing this method. Specifically, it focuses on seeking a theory that does not currently exist, rather than merging existing theories into one (Luna-Reyes & Andersen, 2003). Therefore, this method pursues knowledge that we already possess. We understand the individual elements and their interactions from various studies; we simply have not yet synthesized this information. Thus, we require a method that can built on the existing theories.

[1]At this stage, it might be helpful to define the word ‘theory’. A theory “makes general assumptions about the causal relationships between concepts" (Cairney, 2013, p. 2). This differs from a framework, which is aimed at simply identifying concepts on the basis of analysis of existing research (Cairney, 2013). In this particular case, the theory to be developed will describe the causal relations between the elements as named by Ortt & Kamp (2022).

The use of hermeneutics as a method poses a similar problem. Hermeneutics tries to harmonize contradictions within existing written information.[2] It thereby focuses on placing these texts within the cultural context in which they were produced (Luna-Reyes & Andersen, 2003; Mallery et al., 1986). This approach thus presupposes that the contents of the texts should be subjected to doubt. Although doubt is crucial to scientific inquiry, it is unnecessary to prioritize it as the central objective of this study, given that the information used comes from peer-reviewed papers that convey scientifically proven theories.

In conclusion, the method used in this study should aid in building a theory that shows the fundamental behavior underlying the TIS. However, this theory can be derived from existent, proven theory and therefor does not have to be built from the ground up.

2.2. The Synthetic Method

I have not found an existing method within SD that is capable of doing so. Therefore, I had to broaden my perspective to include other scientific disciplines. Thus, I encountered a suitable theory known as 'synthesis'.[3]

Synthesis is broadly defined, given its use across various fields, but the definition that best aligns with this study is provided by Cairney (2013, p. 2), who states that synthesis "combine[s] the insights of multiple theories, concepts, or models to produce a single theory". In practical terms, this means that the new theory developed in this study will integrate existing research specific to the dynamics of TISs. The challenge with this method lies in its flexibility, as there is no unified protocol for its application. However, there are guidelines that can help ensure that the findings are scientifically sound. Cairney (2013) suggests formulating several hypotheses on the overarching theory and subsequently testing these hypotheses. In this case, we would formulate several hypotheses on what behavior the individual elements and the TIS in general display, which are represented in the form of an SDM.[4] To test these hypotheses, we will apply methods commonly used in SD for examining theory on systemic behavior.

To formulate these hypotheses, we need to review existing research on Technological Innovation Systems. However, it is impractical to cover all available literature. Thus, we must establish criteria for selecting the right sources (Feldman, 1971). To determine these criteria, we need to align with our research goal, which is to develop a SDM that accurately depicts the interactions among elements within the TIS and that identifies the behavior that hold back the transition from the adaptation to diffusion phases. Subsequently, we need to gather information on the elements and their interactions across different phases, aligning this information in a way conducive to modeling.

The initial step is relatively straightforward: selecting literature that explains the elements within the TIS and their systemic behavior. This information is likely found in case studies and existing SD research on innovation systems. However, this still leaves us with a considerable amount of literature to review. To narrow down our selection, we introduce a second criterion: the theory must lend itself to modeling. Consequently, it must meet certain standards, such as providing workable definitions for all elements that can be reformulated as variables that can be measured and treated consistently throughout the

[2] Its origin can be found in the examination of the Bible (Luna-Reyes & Andersen, 2003).

[3] Synthesis is an age-old method that was for example fundamental to the way medieval people treated knowledge. C.S. Lewis describes this with some humor in his book *The Discarded Image*. He says: "At his most characteristic, medieval man was not a dreamer, nor a wanderer. He was an organiser, a codifier, a builder of systems. [...] There was nothing which medieval people liked better, or did better, than sorting out and tidying up. Of all our modern inventions I suspect that they would have most admired the card index." (Lewis, 1964, p. 10).

[4] This means that the model that will be developed through this method is not a certain, but an expected reflection of the behavior of the TIS. Thus, the SDM is a hypothesis in itself that needs to be validated.

model (Luna-Reyes & Andersen, 2003). Central to this criterion is the need for a practical, consistent definition. Therefore, when evaluating competing theories on element definitions, we prioritize those that are measurable and can be represented as stocks, flows, delays, or general variables. This approach means that instead of aiming to integrate all existing research, we select information based on its suitability for inclusion in a SDM.

When we have formulated the hypotheses, we have to test them. For this, we will follow two methods commonly used in SD: interviews and experimentation. The synthesis method heavily relies on the modeller and her cognitive processes. She is the one who selects the literature and combines the different theories (Feldman, 1971). Therefore, it is crucial to validate the findings obtained through this method. This can be done through the use of interviews. By asking an expert to check the behavioral patterns that were found while analyzing case studies, it is possible to validate those patterns. Luna-Reyes & Anderson (2003) name an example where the researcher prepared a workbook containing the behavior of the key variables in his model. He then presented his findings to experts in interviews and asked them to comment on their feasibility. By analyzing the answers, he could formulate a comprehensive list of the main strengths and weaknesses in his conceptualization, that he could then use to refine his model. Another method to test the hypotheses is to build an SDM that consists of all the variables and their links that were found in the literature, followed by experimentation on that model. For instance, when existing research is inconclusive about the presence of a particular connection, we can simulate the model both with and without that connection to observe how the system's behavior is affected. Thus, we can research the behavior of the system by adding or omitting certain variables and links, strengthening or weakening certain feedback loops or by lengthening or shortening delay times (Forrester, 1992). In doing so, we will particularly focus on identifying changes that lead the system to transition from the adaptation to the diffusion phase, thereby addressing our primary research question.

In conclusion, when devising an SDM to illustrate the fundamental behavioral patterns identified in TISs, we have to use a method that can combine the different existing theories on the individual elements and their interactions into one consistent theory. This is where synthesis comes into play. It helps us by asking us to formulate hypotheses based on existent literature. These hypotheses can subsequently be tested using expert interviews and experimentation.

2.3. The Three Levels of the Research Method

The first challenge of this method lies in formulating the synthetic theory. The subquestions already provide an outline of the various aspects that the theory must encompass. These sub-questions can be divided into three levels. The first level focuses on the overall behavior of the system, the second level delves into the interactions among elements, and the third investigates how the individual elements can be defined.

The approach adopted here follows a top-down methodology. This means that we initially focus on understanding the overall behavior of the system, only delving into specifics if necessary. This differs from the conventional SD method, which typically aims to model the entire system comprehensively to identify all key drivers of behavior (Sterman, n.d.). However, innovation systems, as well as economic systems in general, tend to be extensive and complex. Therefore, it is more effective to model specific parts of the system that are essential to achieve the research objectives rather than attempting to model the entire system. This approach aligns with the Delft method of SD, which emphasizes modeling the problem at hand rather than the entire system (Auping et al., 2023). Adopting a top-down approach helps prevent getting overwhelmed by details and ensures focus on the primary research goals.

2.3.1. Fundamental Behavior

At the highest level of aggregation, the theory should illustrate the behavior of the system as a whole. From a technical standpoint, this implies that the researcher should be able to draw a graph that shows the adoption of an innovation over time. She should then create a model that, from a purely technical standpoint, generates that graph. This represents a highly mathematically-oriented approach to modeling. However, the challenge with this method lies in the fact that each TIS exhibits its own pattern of adaptation and diffusion. Also, when researchers study the diffusion of innovations, they each tend to define diffusion differently. They focus, for example, on the legitimacy of the innovation or the number of resources within its network (Binz et al., 2016; Musiolik et al., 2012). Consequently, it becomes difficult to distill one general graph from all these cases.

Another approach to conceptualize the system as a whole is to examine SDMs of innovation systems developed by other researchers. These models depict various aspects of the innovation system, although they may differ from the one we aim to construct, because they focus on different subsets of elements. Examples of these models can be found in Repenning (2002), who was the first to construct an SDM of an innovation system and Walrave & Raven (2016) who have an interesting way of modeling network resources. These models, along with others, can serve as inspiration for understanding the relationships between variables, modeling techniques, and the behavioral patterns generated by the model.

2.3.2. Interactions Among Elements

When this fails, we can look at the system on a more detailed level. We can investigate how the variables proposed by Ortt & Kamp (2022) interact with each other in the system. It is crucial to have this perspective to understand how all the elements are connected. To aid this research, several techniques can be used. Graphs can be drawn to show behavior across time and Causal Loop Diagrams (CLDs) can be constructed to understand the connections between the variables. CLDs can also show the feedback loops and time delays in the system. Also, if we are looking specifically for stocks and flows, we can employ Stock-Flow Diagrams (SFDs) (Auping et al., 2023). However, insights into the interaction between variables are frequently derived from case studies focused on specific elements.

2.3.3. Individual Elements (and their Variables)

Thus, we arrive at the most detailed level of the research method, where we research individual elements. The first step in researching individual elements is finding a definition (see also sub-question 3[5]). This definition should give an unambiguous idea of what the element consists of and how it can be measured (Luna-Reyes & Andersen, 2003). Once this definition is established, we can start looking for the behavior of the elements. The techniques to find this behavior are similar to the techniques used to understand the relations between the elements. Namely, the use of graphs, CLDs and SFDs to display the general behavior of the element and the interactions between the components that make up the elements. For example, a network consists of several actors that are all linked at certain points in time. A graph can be drawn to look at the change in the number of actors in the system over time, and a CLD can be made to show the causal links between the actors.

When the definition and behavior of the individual elements is clear, this information can then be taken

[5]What behavior do the individual elements display, and how does this behavior influence the behavior of the other elements in the TIS?

to a higher level and added to the understanding of the system as a whole. If there is uncertainty about the observed behaviors or a need to explore new directions, guidance can be sought from experts across all three levels. A summary of these levels is provided in Figure 2.2. It shows that we move top-down, beginning at the system level and ending at the level of the individual elements. Moving top-down is relatively straightforward: if necessary information is lacking at a certain level, we delve deeper into the specifics. Conversely, transitioning from bottom to top presents challenges. As previously noted, it is impractical to exhaustively review all literature on individual elements, we therefore impose constraints. Firstly, the literature must present theories adaptable into quantifiable variables, as outlined in §2.2. Secondly, research on a single variable should not exceed one week. Once a theory is identified or the allocated time elapses, the gathered data on the element's behavior is incorporated into the overarching understanding of the system at the level of interactions among elements. Once these have been researched, we can move from this level to *Fundamental behavior*. At this point, we will have a comprehensive model that encompasses all elements within the TIS and their interactions.

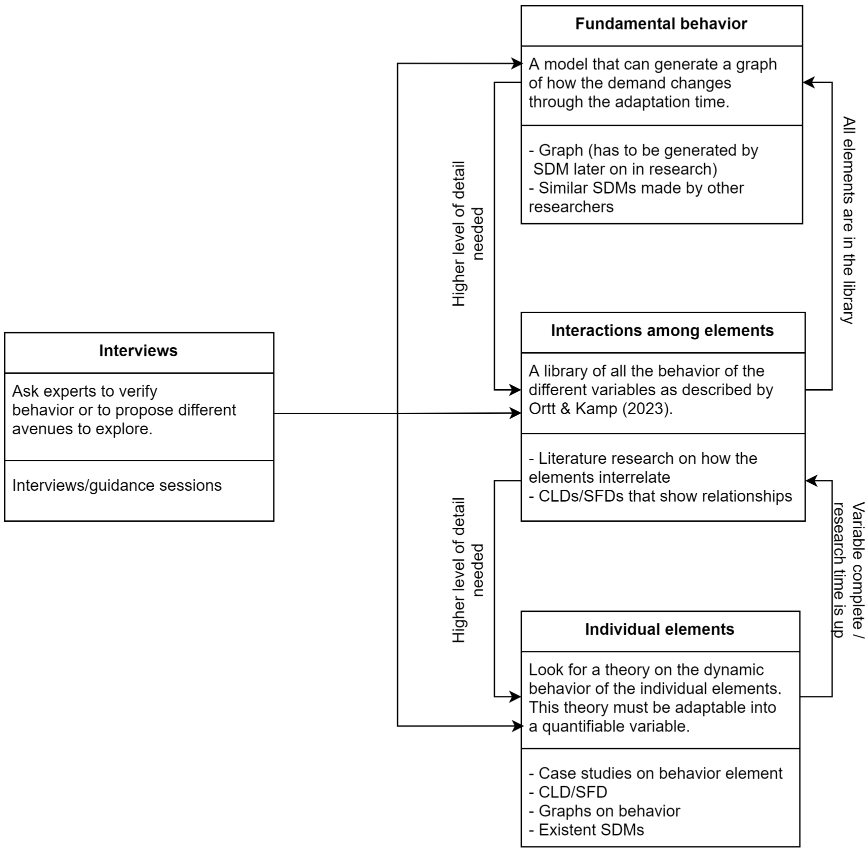

Figure 2.2: The three levels

2.4. Overview of the Method

Once again, the aim of the method is to develop a single theory that clarifies the fundamental behavior. As readers may have noticed, this method has been carefully crafted for this research endeavor. It represents a fusion of various methodologies drawn from different disciplines, combined and organized to produce a method capable of offering a scientifically robust response to the research question. This implies that we have undertaken two key actions. Firstly, we have identified several research techniques, such as the synthetic method, graphs, CLDs and SDFs, and interviews and experimentation. Secondly, we have systematized these techniques, placing them at different points in the research to ensure that they can each fulfill their role within the overarching methodological framework. Figure 2.3 shows how the method was developed in the previous paragraphs. We started with the goal of finding a method that could combine the empirical knowledge on TISs with the methods used in SDM to find the behavior of the system. We selected synthesis for this purpose, because it is able to combine existent knowledge into consistent hypothetical theories. In our method, this is done in three consecutive steps. First, by reviewing a selection of literature that defines the elements and their interrelations in a manner that allows for modeling. Secondly, by developing hypotheses, or a model, of the behavior of the system as a whole through the three levels. Lastly, by validating these hypotheses through expert interviews and experimentation with the SDM.

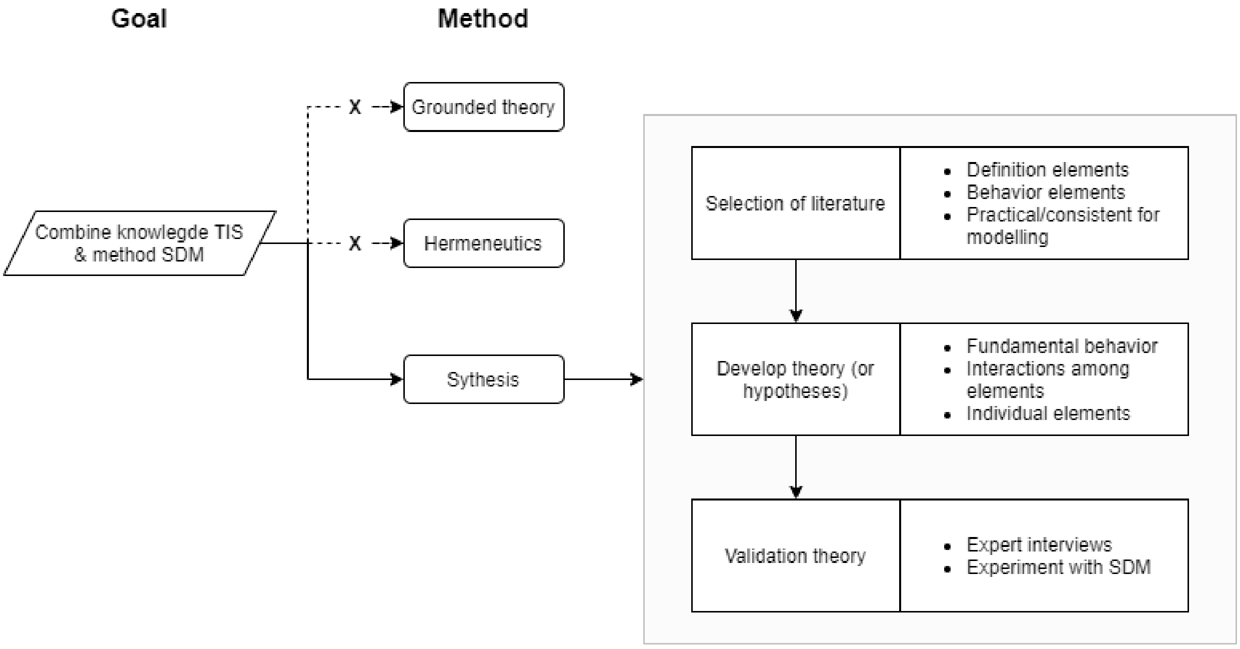

Figure 2.3: Outline method

2.5. Conclusion

The aim of this chapter was to answer the following research question:

> How can the existing information on the TIS be analyzed in such a way that it unveils the dynamic behavior of the system?

Initially, we anticipated achieving this by integrating TIS literature with analytical techniques from SD. However, we found that SD lacked a suitable method for consolidating existing theories into a unified understanding of system behavior. Consequently, we had to explore other scientific disciplines for an appropriate approach. Our search led us to the synthetic method, which aims to synthesize multiple theories into a single coherent framework. However, this method needed modification to fit our specific research context.

Our adapted approach involves formulating hypotheses that manifest as a model depicting the combined behavior of all system elements. We employ a top-down methodology, investigating the behavior of individual elements through various analytical tools such as definitions, graphs, CLDs, and SFDs. Subsequently, we assess how these elements can be translated into variables and integrated into the model of the entire system. Expert interviews and experimentation serve as means to validate and refine our hypotheses, enabling us to understand how system behavior evolves with the inclusion or exclusion of variables and links. In conclusion, through an adapted synthetic method and a top-down approach, we aim to construct a comprehensive model that illuminates the dynamic behavior of TISs.

3

The Dynamics of Technological Innovation Systems

The aim of this theory chapter is to gather information on the TIS building blocks that can be used to construct the system dynamic model. This is done by (partly) answering two of the research questions, whereby each question is aimed at uncovering a certain kind of information that is needed in the model. The questions are as follows:

1. How can the elements in the TIS as summarized by Ortt & Kamp (2022) be defined as quantifiable variables?

For this question, we will focus on the individual building blocks and aim to identify a consistent definition for each one across the literature. Additionally, we will quantify these elements, enabling us to simulate their behavior in a model.

2. What behavior do the individual elements display, and how does this behavior influence the behavior of other elements in the TIS?

To answer this question, we have to investigate the behavior of the individual elements within the TIS. We will employ the *Three levels*-method, as outlined in §2.3. This approach involves examining case studies to identify the variables and their interrelations that define these elements. Specifically, in line with the System Dynamics method, we will focus on feedback loops, delays, and archetypes. This will be achieved by creating causal loop diagrams, stock flow diagrams, and graphs illustrating the elements' behavior. These diagrams and graphs will be combined into textual definitions of the variables and their behavior and a conceptual model.

First, §3.1 clarifies some design principles. Then, Paragraphs 3.2 to 3.6 provide a description of the system and the design of the model. This is followed by §3.7, which addresses the first question, and §3.8, which aims to answer the second question. An explanation of the shapes used in the diagrams can be found in Appendix A.

3.1. Design Principles

Before designing the system, it is essential to outline a few guiding principles for the conceptual model. First, unlike Ortt & Kamp (2022), who argue that all elements in the TIS can either be present or absent and that all must be present for diffusion to occur, we assume that all elements exist to some degree at all times. However, for diffusion to take place, these elements must reach a certain threshold, that might differ depending on the market in which the diffusion occurs. In short, we shift from a binary or nominal scale to a ratio scale[1] Second, we clarify the assumptions for each element to emphasize that the model reflects both the modeler's perspective and the available information and could be designed differently.

3.2. Customers

As previously mentioned, the aim of this paragraph is to understand the buying behavior of customers over time when a new innovation enters the market. This question was famously first posed by Rogers (1962), who concluded that a single innovation in a single market diffuses according to an S-curve, as depicted in Figure 3.1. Whereby each point on the graph represents the cumulative number of customers at that given moment.

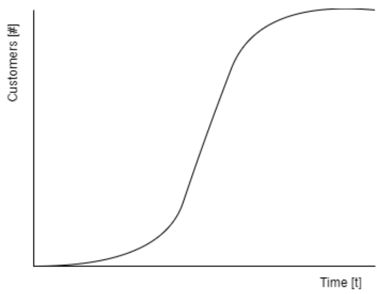

Figure 3.1: S-curve based on Rogers (1962)

This research was later expanded by Bass (1969), who shifted the focus from the cumulative number of customers to the change in new customers over time. This resulted in the graph shown in Figure 3.2.

Figure 3.2: Change in timing of adaptation from Bass (1969)

The behavior shown in both Figure 3.1 and Figure 3.2 stems from a theory on customer interaction developed by Rogers (1962), which devides the market potential of an innovation into two groups: innovative and imitative customers.[2] Figure 3.3 depicts the differing behaviors of innovators and imitators throughout the lifecycle of an innovation. Innovators are drawn to products for their novelty,

[1] This is further explained in §3.6.

[2] The market potential, or number of potential customers in a market, will be regarded as a constant in this model due to the existence of heterogeneous markets, which will be explained in Chapter 4.

while imitators adopt the product only after it has been validated by others. This dynamic is illustrated by the sharp increase in Figure 3.1 and Figure 3.2, where innovators provide a basis that attracts imitative customers who fuel further growth. Eventually, this growth slows or halts when the innovation approaches its full market potential.[3]

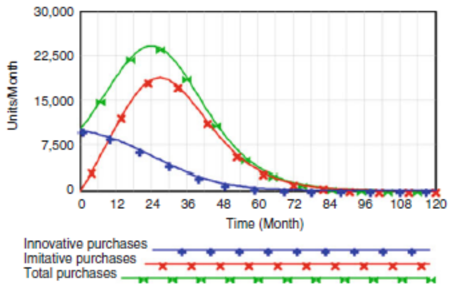

Figure 3.3: Innovators and imitators from Milling & Maier (2020)

This dynamic between innovators, imitators and market potential as determined by Bass has been adopted into a system dynamic model by Milling & Maier (2020). The following equation forms the basis of that model:

$$S_t^{total} = S_t^{inno} + S_t^{imit} = \alpha \cdot (N - \sum_{t=0}^{t-1} S_t) + \beta \cdot \frac{\sum_{t=0}^{t-1} S_t}{N} \cdot (N - \sum_{t=0}^{t-1} S_t). \tag{3.1}$$

Firstly, Equation 3.1 asserts that the total current sales consist of both innovative and imitative purchases. Secondly, the innovative purchases amount to a fraction α of the remaining market potential N minus the cumulative number of previous purchases. Lastly, the imitative purchases constitute a fraction β of the remaining market potential, adjusted by the percentage of the market that has already been saturated. This results in the Causal Loop Diagram (CLD) depicted in Figure 3.4. This model shows the relations that are also mentioned in the formula, whereby the market potential is split between possible innovative and imitative purchases.[4] Whether these potential customers buy the product is dependent on the variable *Probability of purchase*. This creates an avenue in the model for other elements to influence the chance that a product is purchased. Milling & Maier (2020), who originated the idea, have used it to include factors such as competition, capital investment, cost, and price effects.

Figure 3.4 also highlights a feedback loop (C1), which shows that a growth in total demand leads to an increase in the number of imitative purchases. This is in line with the definition of imitative purchases and with Equation 1.

[3]Figure 3.1 and 3.3 show a market in which all customers have adopted the innovation, whereas Figure 3.2 only shows a lowering of the number of sales. This is due to a difference in assumptions between Rogers and Bass. Where Roger assumes that one customer can buy a single product, Bass' model also includes possible repurchases of the same product (Bass, 1969; Rogers, 1962). Rogers' assumption is adopted by Milling & Maier (2020). Our model will be based on Roger's assumption, but can be easily adopted to Bass' assumption by changing the definition of *Market potential* from the number of potential customers to the number of potential purchases.

[4]Also known as respectively α and β in equation 1.

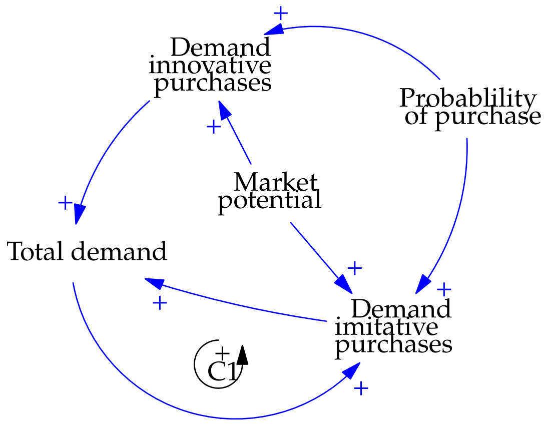

Figure 3.4: CLD customers from Milling & Maier (2020)

This model will build on Roger's foundational differentiation between innovative and imitative customers to explain customer behavior. We will enhance this framework with Milling & Maier's model, adapting their approach by focusing on the variable *Possibility of purchase* while excluding their specific factors and incorporating our own building blocks. In the following paragraphs we will slowly add to the CLD on customers, see Figure 3.4, by integrating the building blocks.

3.2.1. Assumptions

1. The market potential is determined by the number of potential customers instead of purchases.
2. The market potential remains constant.
3. All building blocks, except for customers, influence the demand through *Probability of purchase*.

3.3. Production, Performance & Price

According to Kemp *et al.* (1998), customers have two primary demands when it comes to innovations: the technology must meet their needs and the price must be acceptable. Therefore, our model should first be expanded to include performance and price. However, examining price inevitably leads us to costs and thus production. Given this close interrelation, the three elements are discussed together here.

3.3.1. Production

When an innovation first exits the development phase and enters the adaptation phase, becoming available to customers, its price is often quite high. This is partly due to low production volumes, which result in high production costs per unit. Additionally, it is because the production process itself is still underdeveloped. With each batch produced, the knowledge on how to manufacture the product more efficiently and cost-effectively increases, ultimately lowering the price. This process is known as learning-by-doing (LBD) (Arrow, 1962). Figure 3.5 illustrates this mutual influence between production and cost, whereby the variable *Production cost* represents the effect of LBD and the direct link between *Production volume* and *Production costs per unit* represents the benefits of economies of scale. This *Production cost per unit* influences a cost price, which in turn shapes the product price.

Figure 3.5: CLD production

3.3.2. Performance

The performance of an innovation can be increased by investing in knowledge development. This can be split up into two categories, learning-by-doing (LBD), which is linked to production, and learning-by-searching (LBS), which is traditionally known as Research and Development (R&D) and relates to the generation of new knowledge (Malerba, 1992). A case study by Bildik *et al.* (2016) on the development and diffusion of wind turbines illustrates that, as shown in Figure 3.6, LBS mostly takes place in the development phase and levels off in the adaptation phase, whereas LBD takes of when the innovation enters the market and flattens off when the innovation approaches its final form.

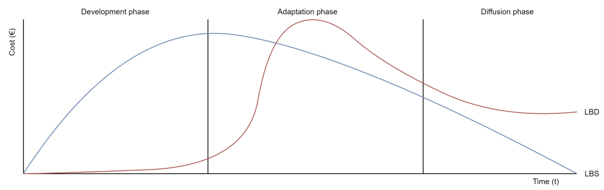

Figure 3.6: LBS and LBD based on Bildik *et al.* (2016)

This means that performance is influenced by investment in both LBS and LBD. It also means that performance is closely linked to price. First, because, whilst LBD can be seen as a positive externality, LBS requires investment. Thus, R&D is a cost. Secondly, a high price will lower the investment risk, thus making investment in the R&D of a technology a more attractive option (Milling & Maier, 2020).

3.3.3. Price

The price in this system exhibits oscillatory behavior due to a phenomenon known as the pig cycle. This cycle suggests that companies increase production when prices are high, leading to market saturation when the new batch is introduced, subsequently lowering prices. In the model, this dynamic is represented as a feedback loop between price and production (Auping et al., 2023).

3.3.4. Causal Loop Diagram Production, Performance & Price

Incorporating the variables and relationships discussed in the previous paragraphs results in the CLD depicted in Figure 3.7. The hexagon represents the subsystem *customers*, which is represented in full in Figure 3.4.

The CLD also includes the following six feedback loops:

- P1: An increase in demand results in a lower cost price per unit, which leads to a higher probability of purchase.
- P2: Represents the pig cycle, where a higher price leads to a higher expected turnover by the suppliers, which leads to an increase in the production volume, which results in oversupply and a lower price in the next cycle.
- P3: Another representation of the pig cycle. However, in this case the higher production volume leads to a lower overall production cost, due to learning-by-doing.
- P4: A higher price leads to more investment in R&D, but that also results in a higher cost price, as the investment also has to be recovered.
- P5: Similar to P1, however in this case it is not the price that influences the probability of purchase, but the performance, which increases, when the investment in R&D increases.

- P6: The production volume also more directly influences the probability of purchase through *Performance*, as LBD does not only lead to a lower production cost, but also to improvements in the product itself.

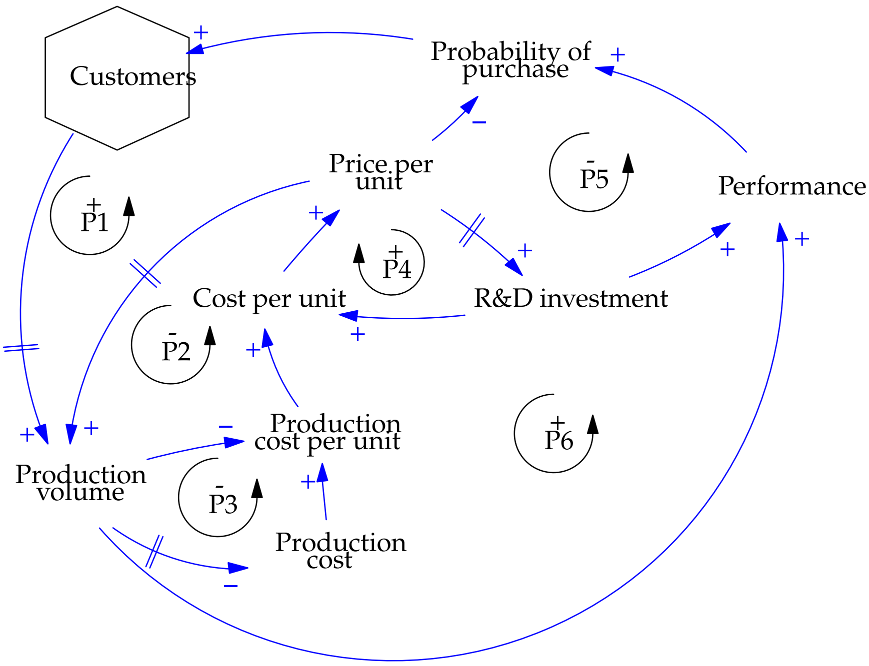

Figure 3.7: CLD price, production and performance

3.3.5. Assumptions

1. In this model, supply always meets demand, be it with a delay. This is expressed in the link between *Total demand* (which is depicted as the building block *Customers* in Figure 3.7) and *Production volume*. This link cannot be slowed down or cut off by an external factor such as *Production capacity* or *Budget limitations* which could create a discrepancy between supply and demand.
2. The model only displays a change in the *Production volume*. It does not take the development of the production system that might result in an increase in volume into account.

3.4. Networks

Next to the more economic and technical parts of the system which were mentioned in the previous paragraphs, TISs are also largely determined by different actors and organizations. On the supply side of the system, in which the technology is developed and produced, these actors include, e.g., different kinds of firm, research institutes, producers, distributors and actors who provide complementary products and services (Musiolik et al., 2012; Ortt & Kamp, 2022). These actors are often linked in a network.[5] These networks can be informal; in this case there are interpersonal ties that lead to collaboration, which is mostly limited to knowledge sharing (Granovetter, 1973; Musiolik et al., 2012). However, networks are

[5]Networks also exist on the demand-side of the system between customers and suppliers. Yli-Renko *et al.* (2001) for example mention the possibility of gaining knowledge through these networks and consequently improving the performance of the innovation. However, since most of the literature, including Ortt & Kamp (2022), focuses on supply-side networks and to keep the model manageable, demand-side networks will not be included.

also often formal, which means that they have an organizational structure, clearly identifiable members, and common objectives. These formal networks often go beyond merely sharing knowledge; they also engage in collective action and contribute to system building (Musiolik et al., 2012).

3.4.1. Modeling Choices: Formal Networks and Resources

To be able to model these networks, two fundamental choices were made, both based on Musiolik *et al.* (2012) and inspired by Walrave & Raven (2016). First, instead of modeling the number of actors in the network and their ties, we will model their (combined) resources. Secondly, we will model formal instead of informal networks. The reason for to model resources is two-fold. The main one is that the aim of this study is to see how the building blocks together create the behavior of the system. In case of the networks, this means that we want to know how big their influence is on this behavior. This cannot be measured in the number of actors in the network or the number of ties that exist between them, because these actors and their ties are highly heterogeneous. They differ both in importance and in what they contribute (Granovetter, 1973). Thus, to measure the influence of the network on the system, we have to know what these actors offer the network in terms of resources. Another reason to choose resources over links is to reduce the complexity of the model. Whilst resources can be added up, actors would have to be modelled as individual variables, which would significantly increase the size of the model. Secondly, we will only model formal networks. On the one hand, as previously mentioned, because formal networks have more power to build the system than informal ones. A model of an informal network would therefore include less, and other, variables and would mostly be centered around knowledge sharing. To model the influence of networks, we should model them at their most influential, which is as a formal structure. The second reason for this decision is that formal networks are more easily identifiable and that the data on the resources of formal networks is more readily available than on informal ones. In short, this model will be based upon formal networks and their resources.

3.4.2. Organizational, Network and System Resources

In the literature, resources have mostly been limited to assets needed to develop a technology, such as investment capital needed for R&D. However, resources of innovation networks go beyond externally attracted investments, as networks themselves can also generate resources. To include this distinction, Musiolik *et al.* (2012) differ between three kinds of resources: organizational, network, and system resources.

Organizational resources are specifically developed within the content of the organization. They can be both tangible and intangible and can be used by an organization to implement strategies to further the development, adaptation, and diffusion of a technology. Tangible resources include financial assets and equipment, while intangible resources focus on aspects such as the knowledge, culture, and reputation of an organization. In contrast, network resources are developed within networks of organizations, and they focus on the relationship between the actors. Thus, they include common aims and trust amongst the actors (Musiolik et al., 2012). If the network is managed well, and there is a high level of collaboration, it will become more effective (Smart et al., 2007). Which means that it will create more system resources, which are assets that are collectively produced beyond the boundaries of a single organization, to support the technology and its surrounding innovation system (Musiolik et al., 2012). Examples of system resources are shared patents or production guidelines (Musiolik et al., 2012; Smart et al., 2007). System resources can also be created by autonomous actors. An organization can for example decide to share its knowledge or firm can work towards increasing the reputation of the technology, the results of which are shared by the entire system (Musiolik et al., 2012). In our model we include both the contributions of the organizations and the networks towards system resources.

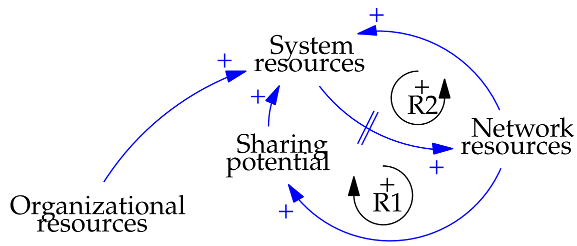

Figure 3.8: CLD organizational, network and system resources

Figure 3.8 shows the relationships between organizational, network and system resources. As previously stated, system resources are an accumulation of organizational and network resources. Organizational resources add to the system resources by transferring resources from the organization to the system. The amount of resources transferred depends on the variable *Sharing potential*, which is the percentage of resources the organization wants to share with the network. This percentage is influenced by the strength of the network, as more trust within the network will lead to more collaboration, and thus a higher sharing potential (Musiolik et al., 2012). The network resources themselves are influenced by system resources, as a strong system created by a network, will often in turn strengthen that network (Granovetter, 1973). The network resources are influenced by a delay, because the longer a network exists, the more effective it becomes (Musiolik et al., 2012). This often follows a pattern of initiation and growth, followed by stabilization, also known as an S-curve (Smart et al., 2007).

Figure 3.8 also shows two positive feedback loops. The first (R2) shows that there is mutual causation between *System resources* and *Network resources*. The second (R1) demonstrates that more system resources will lead to more organizational resources, such as trust, which in turn will encourage organizations to share their resources with the system.

3.4.3. Networks Within the Technological Innovation System

An expansion of system resources can influence the TIS in two ways; it can increase the amount of shared expertise (*Joint knowledge*) and the amount of power and reputation (*Joint power/reputation*). This knowledge consists of two kinds of insights: learning as acquisition and learning as participation. Acquired knowledge is knowledge that is directly transferred from an organization to the system and participatory knowledge is gained through the existence of the network, such as shared patents (Célia & Marie-Benoît, 2023; Smart et al., 2007; Yli-Renko et al., 2001). This can be seen in Figure 3.9, where the organizational and network resources strengthen the system resources, which in turn produce joint knowledge. This joint knowledge influences two parts of the system; the production and performance. This can be viewed as a form of learning-by-doing and learning-by-searching that is provided by the network. In the case of *Production*, the new knowledge can be used to increase the production volume and decrease the production cost. System resources also produce joint power and reputation, which can create or change institutions (Musiolik et al., 2012). Lastly, the network is influenced by the larger system through *R&D* investment. R&D can be done within the organization and within the network. However, as knowledge can only be produced once, it is more cost-effective to do combine R&D activities in a network (Goyal & Moraga-Gonzalez, 2001). We will therefore assume that an increase in *R&D*

investment will lead to an increase in *System resources* instead of *Organizational resources*. This results in the interesting new feedback loop N1, which shows that in the long term investment in joint knowledge can lead to less investment in R&D, due to lowering price, which in turn impacts the system resources. This can be explained by means of Figure 3.6, which shows that over time, when the technology enters every larger markets and the innovation approaches its final form, R&D, or LBS, also naturally declines.

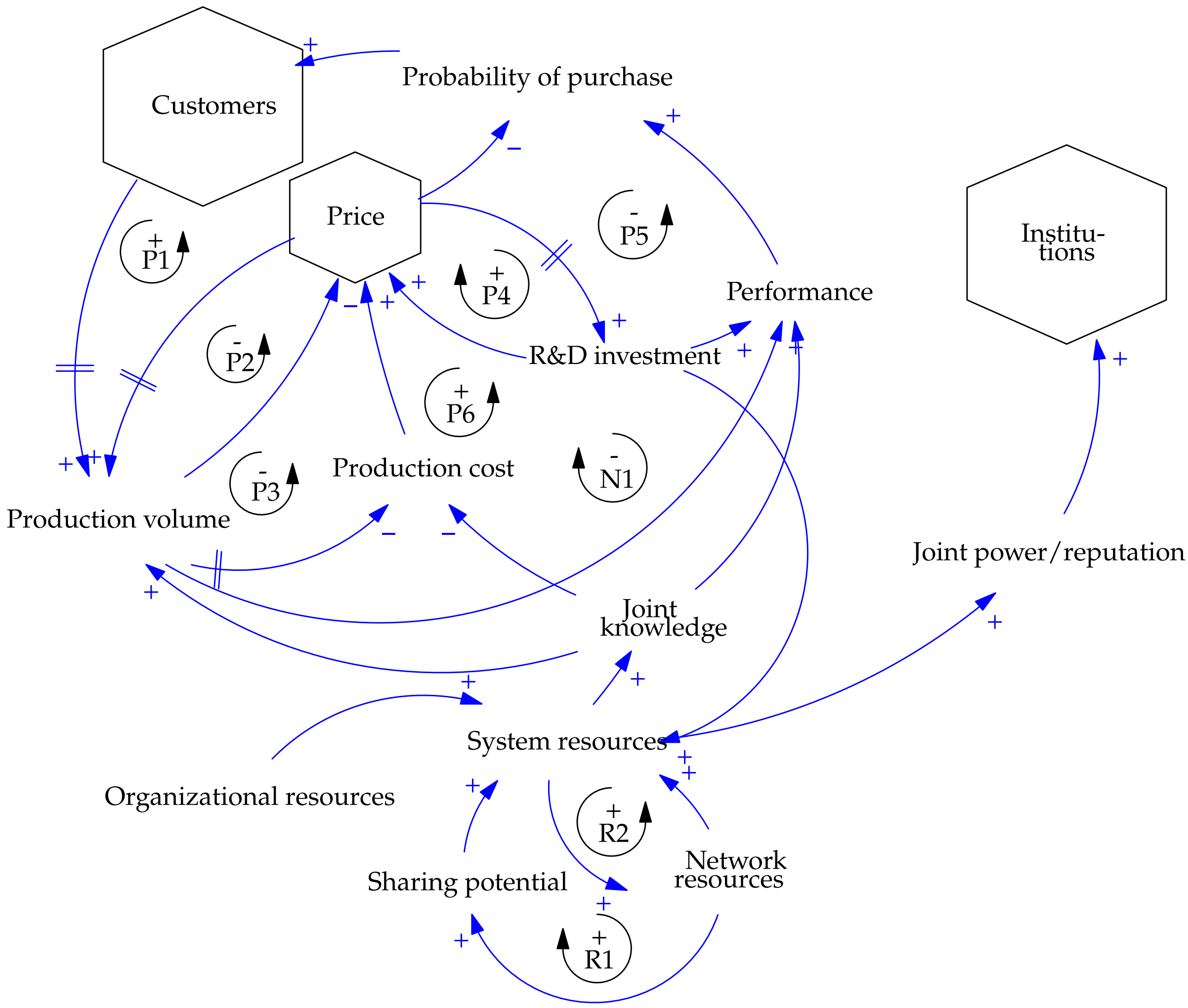

Figure 3.9: CLD Networks

3.4.4. Assumptions

1. Only formal, demand-side networks are regarded.
2. The size of the networks is measured in its resources instead of its number of participants.
3. R&D is a system resource instead of an organizational resource.

3.5. Institutions

Institutions are formal and informal rules such as government policies, laws, standards, and regulations (North, 1990). For a technology to succeed and spread in the market, it must either align with the existing market institutions or initiate a process to modify these institutions to better fit the technology.

This is especially challenging for RNTIs, as they tend not to fit in with the exact expectations for technologies around which institutions are built, due to their radically new applications (Jacobsson & Bergek, 2011; Kemp et al., 1998). RNTIs thus pose a greater investment risk than more common technologies and are therefore more often left on the shelf (Kemp et al., 1998). As RNTIs do not fit in with pre-existing institutions, the institutions themselves have to be changed or added to for the RNTI to become successful (Célia & Marie-Benoît, 2023; Kemp et al., 1998; Ortt & Egyedi, 2014). When a technology is or has become compatible with the institutions (a process we will call *Product standardization*) it will be regarded as more trustworthy, thus leading to a higher probability of being purchased by customers (Geels, 2004). To understand this process, two concepts have to be introduced; flexibility and standardization, and legitimacy.

3.5.1. Flexibility & Standardization

Ortt & Egyedi (2014) describe the role of flexibility in the relationship between institutions and RNTIs. They state that the newer or more radically different a technology is, the more it will look to existing institutions for guidance. It will be adapted to fit with these institutions to lower the risk of failing. However, by being very flexible in the beginning and forming itself around the institutions, it will be less flexible in the long term, because it has already molded itself to a set of institutions. Another aspect of this is that when the technology enters the market, the demand-side of the system is not flexible enough to allow for the new technology, which leads to standardization of the product to coerce the customers into buying it. However, as technology increasingly standardizes over time, there is a risk that the demand may suddenly prefer new products with new possibilities. This might mean that the demand changes in a direction that the technology is no longer flexible enough to accommodate (Hanseth et al., 1996). Thus, when aligning the institutions, innovation and demand, two variables play an important role; product standardization and demand flexibility.

We will first discuss the theory behind standardization. There are, in general, three ways in which a technology can be standardized by the system; through de facto, de jure and formal standardization. De facto standardization occurs through the existence of the system and is inherent in market mechanisms (Hanseth et al., 1996). It is closely related to a phenomenon called 'dominant design', whereby technologies in the same class have the same designs for their core components (Murmann & Frenken, 2006). A design becomes dominant when it is accepted as the standard for the industry by both the demand and supply-side of the market. Standards in these markets are often greatly informed by these dominant designs (Hanseth et al., 1996). On the demand-side, these standards are imposed by, for example, including them in tenders. On the supply-side, it consists of the standardization of performance and production processes (Blind, 2016). In our model, this de facto standardization is therefor shaped by *Production volume*, *Performance*, and *Total demand*, as shown in Figure 3.10.

Figure 3.10: De facto standardization

De jure standards are rules and regulations that are enforced by law (Hanseth et al., 1996). In our model these standards fall under the broader umbrella of *Governmental institutions*, as governments can not only influence the system through regulation, but also through subsidies for R&D and by encouraging interactions between the actors in the network, thus creating more *System resources* (Kemp et al., 1998). It is important to recognize that these relationships stem from government policy decisions, meaning their existence depends on these policies and can change. These relations, together with those belonging to de facto standardization, are shown in Figure 3.11.

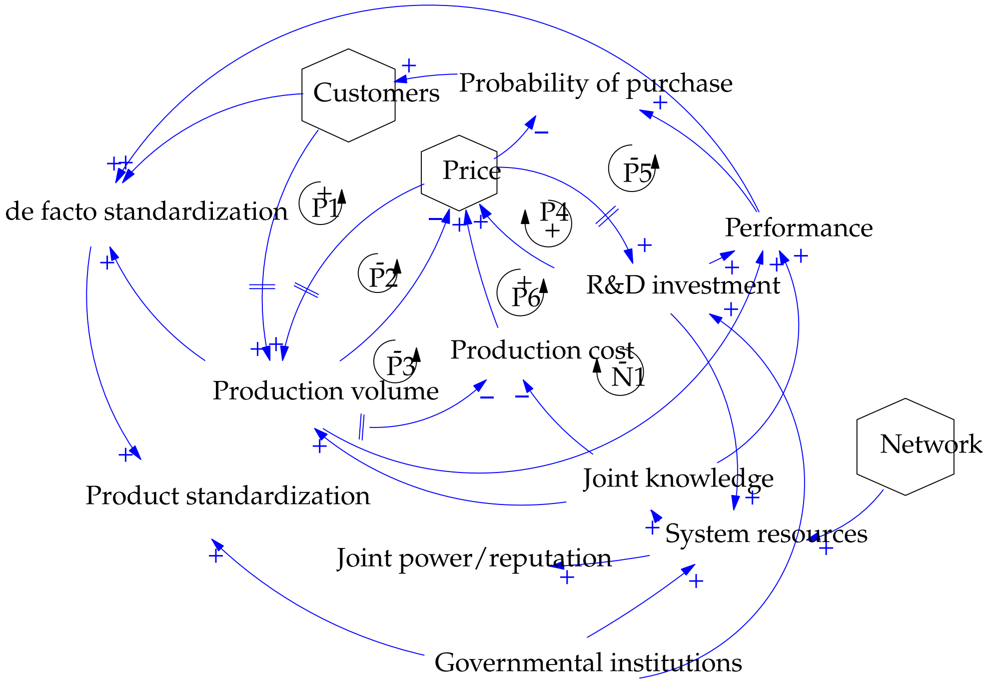

Figure 3.11: CLD De facto standardization and governmental institutions

Formal standards are created by formal networks, such as the *International Organization for Standardization* (Hanseth et al., 1996). These networks can create guidelines, which are informed by their joint knowledge and enforced by their joint power and reputation (Blind, 2016). Their power and reputation can also be used to influence governmental institutions, e.g., petitioning them to adjust their policies (Markard et al., 2016).

In short, there are three ways in which a product becomes increasingly standardized: through market mechanisms, through law, and through guidelines made by formal networks. At the same time, the demand-side of the market remains somewhat flexible or could become more flexible due, for example, to new emerging products or changes in the surrounding landscape of the TIS that lead to new demands (Geels, 2006). This leads to a discrepancy between a product that becomes more and more standardized and a market that might change their demands at any moment. This is where the problem that Ortt & Egyedi (2014), but also other authors, describe, stems from. On the one hand, standardization increases demand, but it also stops innovation, resulting in a lack of inherent flexibility in the design that is needed when the demand changes (Brem et al., 2016; Hanseth et al., 1996; Ortt & Egyedi, 2014). In terms of the model, this means that a high *Demand flexibility* will lead to a lower *Probability of purchase* of this specific product in this TIS.[6]

3.5.2. Legitimacy

As mentioned previously, for an innovation to become successful, it has to be deemed trustworthy by the actors in the system. This ‘trustworthiness’ is called legitimacy. Or, more specifically, product legitimacy

[6] A more comprehensive theory of demand flexibility and a description of its roots in evolutionary economics can be found in Chapter 4.

as experienced by customers.[7] Something, in this case an innovation, is viewed as legitimate when it is more or less oriented towards existent 'maxims' or rules (Weber, 1924). Maxims are "norms, values and beliefs that individuals presume are widely shared, whether or not they personally share them" (Johnson et al., 2006, p. 55). Meaning that legitimacy is related to mass. The bigger the group of people that sees an innovation as legitimate, the more quickly it will become legitimate in the eyes of others. This is a behavior that is similar to Roger's (1962) S-curve that describes the dynamic between innovative and imitative purchases, whereby there is a group of people that accepts the innovation, which inspires others to follow their lead, which leads to exponential growth that is only flattened when the market is saturated, or in this case, when the innovation is seen as legitimate by everyone in the market.

Due to this dynamic, legitimacy is often seen as a byproduct of the diffusion of an innovation. The idea being that an innovation becomes automatically more accepted when the demand grows. However, legitimacy is not only emergent; it is also explicitly given by a society (Markard et al., 2016). Johnson *et al.* (2006) stress that an innovation needs explicitly granted legitimacy when it enters the market, which becomes implicit the more it diffuses. One could say that an innovation is granted implicit legitimacy when it enters the exponential growth-phase of the S-curve and becomes legitimate once this curve ends, as its legitimacy is then 'widely shared'. These changes in the legitimacy are visualized in Figure 3.12.[8]

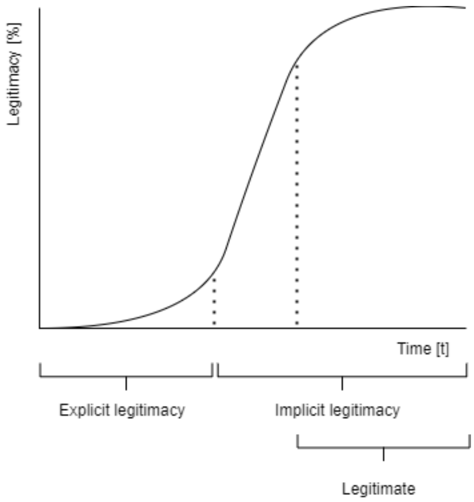

Figure 3.12: Explicit and implicit legitimacy

The fact that legitimacy can be both implicitly and explicitly granted by a society leads to several relations in the model. Implicitly given legitimacy is represented as a link between *Total demand* and *Legitimacy*, meaning that a growth in *Total demand*, will lead to a growth in *Legitimacy* (Dewald & Truffer, 2011). Explicit legitimacy can be fostered in different ways. First, as previously noted, through standardization (Geels, 2004). And secondly, by the networks who can build legitimacy by sharing knowledge through, for example, an outreach campaign. This relationship goes both ways, as a strong network will also react to a drop in legitimacy by trying to gain more legitimacy for their innovation through standardization

[7]We talk specifically about product legitimacy as experienced by customers to avoid confusion, because other parts of the system, such as the network or the institutions, can also be more or less legitimate and other actors, such as suppliers within the network, can also experience the innovation as more or less legitimate. The choice for this type of legitimacy is related to the goal and design of the model, which is to see how the building blocks influence the demand through *Probability of purchase*, see also §3.2. We want to examine how the demand side perceives the product's legitimacy and how this perception influences their decision to adopt the innovation.

[8]Binz *et al.* (2016) used this theory by Johnson *et al.* (2006) as a basis for their case study. This implementation also served as an inspiration for this model.

or outreach (Binz et al., 2016). This creates a balancing feedback loop. An example of this dynamic is the gaming industry in the early '00 in Germany. After several school shootings, these games were scrutinized, which resulted in the lobby for more regulation for these games by the producers. These regulations made the games more trustworthy for the general public, which lead to more legitimacy for the product than there had been before the shootings took place (Binz & Gong, 2022). In short, legitimacy influences the probability of purchase of an innovation and can be implicitly or explicitly granted by customers. Perceived legitimacy can be increased through standardization or networks.

In conclusion, institutions consist of several components. Most notably, de facto standardization, product standardization, governmental institutions, market flexibility and legitimacy. These components and their relations are shown in Figure 3.13. This CLD also brings four new feedback loops to light. The first one (I2) is a reinforcing feedback loop between *System resources* and *Governmental institutions*, which shows that governments and networks over time create an ever closer relationship. The second one (I1) is again a reinforcing loop between *Product standardization*, *Legitimacy* and *Customers*, meaning that the more a product becomes standardized, the more legitimacy it gains, leading to even more standardization. It is interesting to see this feedback loop in relation to the third loop (DF) in the system, related to *Demand flexibility* and *Customers*, because it shows that if the demand suddenly becomes more flexible, for example due to a shock, the *Probability of purchase* will be lowered, even though the innovation had gained high legitimacy. The final loop (I3) is a balancing feedback loop between *System resources* and *Legitimacy*, meaning that a network can create more legitimacy if that is deemed necessary.

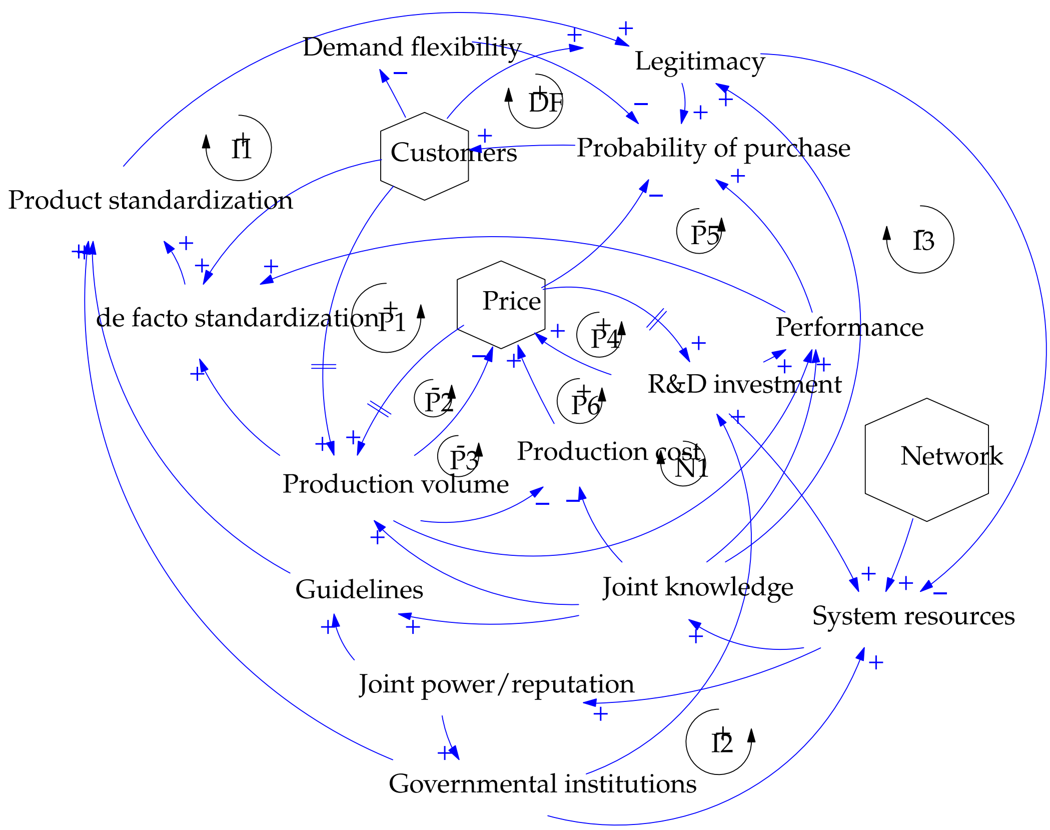

Figure 3.13: CLD Institutions

3.5.3. Assumptions

1. Legitimacy in the model is limited to product legitimacy as experienced by customers.

3.6. Complementary Products & Services

Ortt & Kamp (2022, p. 4) define complementary products and services, or complementarities, as the elements in the TIS "supporting development, production, distribution, adaptation, use, repair, maintenance, and disposal of the innovation". In short, these are the products and services that in one way or another serve the core technology. Whether they are critical or only beneficial for the adaptation of the core product depends on the technology. For example, a car is dependent on a combination of different complementary components in order to drive, whereas a video gaming device does need some games in order to function, but not the wide variety that is available nowadays. When Ortt & Kamp (2022) formulated their building blocks, they wanted to emphasize the fact that each of them was integral to the diffusion of the technology. If we extend this assumption, namely that the technology would instantly fail if the necessary complementarities were not available, to this SDM, *Complementary products and services* would be a binary variable. It could either enable the TIS to function or shut down the system entirely.[9] However, in this study, our aim is to know how the components within the system interact. It is therefore more interesting to see how the non-essential complementarities change the dynamics in the system, than to know whether the essential complementarities allow for the system to exist. For that reason, we will assume that all essential complementarities are present at the start of the adaptation phase.

Before these complementarities become available, they have to be developed. This can be done internally by the same corporation that is responsible for the core product, through a collaboration between this and other firms, fully independently by third parties, and through competition between different complementarities (**VanDenEnde2013ShouldTest**; Breschi & Malerba, 1997). This model will not distinguish between these options; instead, all complementarities will be generated by the network as defined in §3.4. This results in the simplification that all complementarities are developed through collaboration, as we have defined networks as formal associations that engage in collective action. If we were to include all options, we would have to include the element of competition, which is outside this model's scope.[10]

In conclusion, for this model, we will define complementary products and services as the non-essential products and services that aid the adaptation of the core technology and that are created through the collaborative effort of the network. They will be represented by the variable *Availability of CP&S*, which is measured in the number complementarities. The rest of this paragraph will focus on the interactions between this variable and the other building blocks.

3.6.1. Dynamics of Complementary Products & Services

The influence of complementarities extends to the demand-side of the system. Firstly, if it possesses high legitimacy itself, it can enhance the legitimacy of the core product (Reinders et al., 2010). This also implies that a low-quality complementary product will decrease the legitimacy of the core product (**VanDenEnde2013ShouldTest**). For this reason, the variable *Availability of CP&S* should also be able to have a negative value, reflecting the influence of the number of low-quality complementary products

[9] This dynamic is also known as time-to-market and refers to how the timing of the availability of essential complementary products affects the success of the core product (**VanDenEnde2013ShouldTest**).

[10] See also §1.6.

and services on the system. Secondly, the presence of complementary products can make innovation more attractive to a larger group of customers (Adamides et al., 2004). Thus increasing the *Probability of purchase* of the product.[11] Finally, complementary products are often associated with technical interrelatedness, as they are typically linked to a specific core product. An example of this is video games that are playable only on a particular device. This situation leads to high switching costs for a growing number of customers in the system, which in turn fosters greater de facto standardization (Cecere et al., 2014; David, 1985). This dynamic is represented by the link between *Availability of CP&S* and *de facto standardization* through *Total demand*.

Complementarities not only influence the system but are also influenced by it. Van de Kaa *et al.* (**vandeKaa2015StrategiesCommitment**) identify two links in this direction. Firstly, the link between *Total demand* for the core product and the available complementarities. As a rule, a growth in the number of customers leads to an increase in complementary goods. For example, a rise in the use of WiFi led to a boost in sales of complementary goods that utilize this technology. Secondly, if the actors in the network are committed to the core product, meaning that there is a robust network, they will create more complementarities for that innovation. Thus, leading to a strong link between *Network resources*, which includes trust and common aims, and *Availability of CP&S*.

The aforementioned links are shown in Figure 3.14. This figure also shows two new feedback loops. The first (CPS1) demonstrates that the growth of the demand for the core product and the availability of complementarities reinforce each other, which is in line with Van de Kaa *et al.* (**vandeKaa2015StrategiesCommitment**). The second feedback loop (CPS2) shows that this dynamic is further strengthened by the growth of the network through the growth of the demand, which in turn leads to more availability of complementary goods. CPS2 strengthens *Probability of purchase* directly and indirectly through *Legitimacy*.

[11] Adamides *et al.* (2004, p. 1) specifically state that complementary products can "create or increase the size of the market". This implies that the availability of complementary products enhances the variable *Market potential*. However, as mentioned in §3.2, this model is designed such that demand can only be influenced externally through the *Probability of purchase*. Therefore, we will assume that an increase in market size is equivalent to an increase in the *Probability of purchase*.

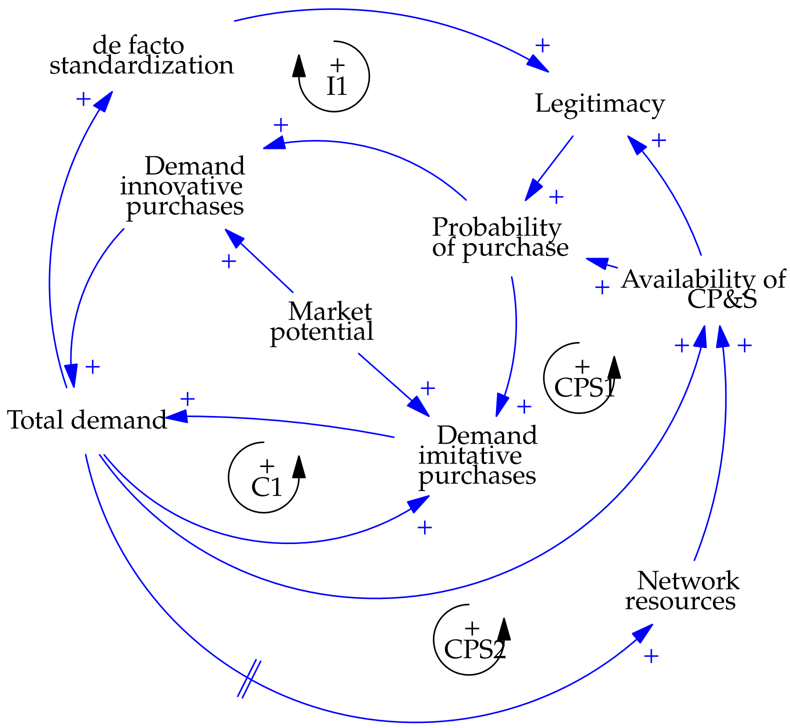

Figure 3.14: CLD CP&S

3.6.2. Assumptions

1. All essential complementarities are present at the start of the adaptation phase.
2. All complementarities are developed by the network and thus through collaboration.
3. An increase in market-size is equivalent to an increase in *Probability of purchase*.

3.7. Conclusions on the Definitions of the Building Blocks and a Case for a Dimensionless Model

The goal of this chapter is to address two sub-questions concerning the definitions and behavior of the building blocks. The behavior will be explored in §3.8, while this paragraph will focus on answering sub-question: '*How can the elements in the TIS, as summarized by Ortt and Kamp (2022), be defined as quantifiable variables?*'.

This question is twofold; it asks for a definition of the building blocks in the form of variables, and it asks for a method of measurement. The first part has been answered in the preceding paragraphs where we have looked at the theory behind each building block, which we have translated into various variables per block. A summary of this can be found in Table 3.1.

Table 3.1: Variables and their definitions

Variable	**Definition**
Customers	
Demand innovative purchases	Demand based on novelty
Demand imitative purchases	Demand based on validation by others
Market potential	All potential customers in the market
Total demand	Total demand for the innovation in the market
Probability of purchase	The probability that a customer purchases the innovation
Price, Production & Performance	
Cost per unit	The cost price of one product
Performance	The extend to which the innovation meets the customers expectations
Price per unit	The market price of one product
Production cost	The total production cost per time unit
Production cost per unit	The production cost of one product
Production volume	The total number of products produced per time unit
R&D investment	Total investment in R&D for the innovation per time unit
Networks	
Joint knowledge	The total amount of expertise shared by the network
Joint power/reputation	The total amount of power and reputation shared by the network
Organizational resources	The total amount of resources developed within the context of the individual organizations
Network resources	The total amount of resources developed within the context of the network
Sharing potential	The percentage of resources the individual organizations want to share with the network
System resources	The total amount of resources created by or handed over to the system
Institutions	
De facto standardization	Standardization through market mechanisms
Demand flexibility	The change in preference of the product on the demand side
Governmental institutions	Total influence of the government over the TIS
Guidelines	Standardization through networks
Product standardization	A combination of de facto, de jure and formal standardization
R&D investment	Total investment in R&D for the innovation per time unit
Complementary Products & Services	
Availability of CP&S	The number of complementary products and services available for the core product

Formulating an answer to the second part of the question is more complex. Examining the definitions of the variables in Table 3.1 reveals that some variables, such as *Cost per unit*, can be naturally assigned a unit, while others, such as *Joint knowledge* or *de facto standardization* have less intuitive units. This opens the discussion of what units to assign where and how to make sure that each of these units are correct and consistent throughout the model (Forrester, 1961). However, the problem with this model is that it is very fundamental and is not linked to a real-life case. As a result even variables that appear to be easily quantifiable are, in reality, too abstract. We do not know how the behavior of the system would change if we were to start of with one instead of a hundred customers, because there is no real example of the diffusion of a particular technology that we could use to validate this behavior.[12] The only thing we know is that certain variables have a certain trajectory. Take for example *Total demand* and *Legitimacy* in Figures 3.3 and 3.12. A way to base the behavior of the model upon these trajectories instead of on specific values is by normalizing the values. In short, this means that one divides the desired value of a certain variable by a reference value in order to determine its effect as an input value on the rest of the system. Consequently, the modeller does not need to know the exact number of new customers in a given period, but rather how this effect would change due to anticipated growth (Sterman, 2000).[13]

A result of only working with ratios is that there is no need to attach dimensions to the variable. This is a known but unpopular approach in system dynamics, because it creates a discrepancy between the reality of the system and the model. Coyle (1998, p. 364) even states that "[w]henever one wants to declare a constant to be dimensionless, one should pause, think carefully, and consult a colleague." Having taken these steps, I believe that in this case, given the high level of abstraction of the model and the focus on trajectories rather than constants with specific values, this choice is justified and even proper.

In conclusion, in the last paragraphs, we have split the building blocks into various variables and defined them. Furthermore, we have discussed why we will not attach dimensions to these variables, thus creating a dimensionless model. With these insights, we have effectively answered sub-question 2.

3.8. A Dynamic Hypothesis of the Behavior of the Building Blocks

In the previous paragraphs, we have defined the building blocks as quantifiable variables, and we studied how they are interconnected. This has resulted in a series of Causal Loop Diagrams that, when combined, form the system shown in Figure 6.2. These diagrams already showed various feedback loops. In this paragraph we will analyze these feedback loops and the further interrelatedness of the system to gain an understanding of its overall behavior. The aim of this paragraph is therefore to answer the fourth sub-question: *What behavior do the individual elements display, and how does this behavior influence the behavior of the other elements in the TIS?*

It is important to note that this question asks for a definitive answer; it wants to know with certainty what the behavior of the system will be. The only way to, at least partly, gain this certainty is by validating the model using expert interviews or computer simulation.[14] The implementation of these methods is unfortunately beyond the scope of this research. Therefore, this study will focus on formulating a hypothesis about the system's behavior, which can be validated in future research.

This paragraph is structured according to the building blocks, which over the last few paragraphs have

[12] It is of course possible to adjust this model in a way that it can be applied to a real-life technology. This would most likely force the modeller to attach dimensions to the variables.
[13] For a comprehensive explanation of normalization, see §5.
[14] See also §2.2.

become subsystems. For each subsystem, we will outline key aspects of its behavior that provide insight into the overall behavior of the system. We will do so using the feedback loops and the relationships between the variables. It is important to note that Figure 3.15 does not display all the feedback loops that were mentioned earlier, nor does it display all possible feedback loops. This was done to make the diagram clearer and because this method of analysis is not suitable for large feedback loops with many variables. The impact of these larger feedback loops becomes apparent only over the long term, necessitating the use of computer simulations to detect its behavior.

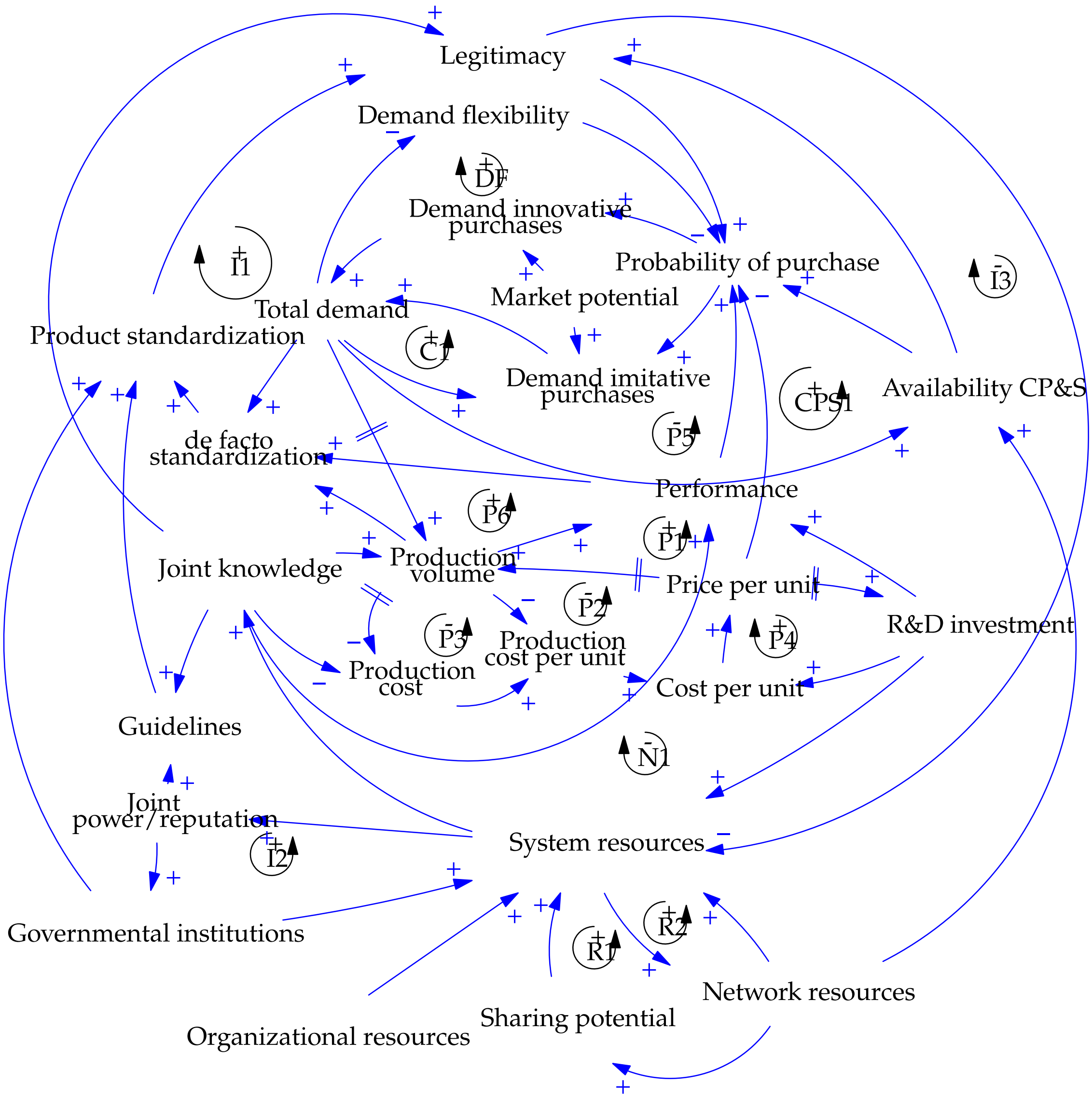

Figure 3.15: Full CLD

3.8.1. The Behavior of Customers

In §3.2, we explored the evolution of the conceptualization of trends in the number of customers in the market. We decided to follow Milling & Maier (2020), who modelled the change in the number of customers over time. This results in a trend which is akin to the one that is shown in Figure 3.16. Interestingly, this figure is also associated with a known archetype in SD-literature called *Limits to* *growth*. This archetype shows that the number of customers keeps growing (*C1(+)*), until it reaches a limit, after which it sharply declines. Here, the limiting condition is the *Market potential*. This implies that our success story, the diffusion of the TIS in the market, carries its own looming tragedy, as once the market becomes saturated, demand will collapse.

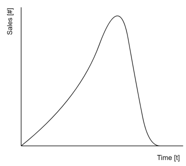

Figure 3.16: Limits to growth

If the demand were considered as a separate entity, the change in the number of customers would follow the pattern shown in Figure 3.16. However, Figure 3.15 illustrates the significant impact that *Demand flexibility* can have on *Total demand*. If demand becomes more flexible, *Total demand* will decrease, whereas if demand becomes more rigid, *Total demand* will increase. Consequently, fluctuations in demand will correct the diffusion pattern depicted in Figure 3.16. It is crucial to note that demand fluctuations are typically long-term changes, meaning that the graph of the number of customers will not abruptly shift to an oscillating curve. Instead, it will affect the graph's trajectory, particularly during transitions between rigid and flexible demand, as the feedback loop *DF(+)* will amplify this behavior.

Examining the impact of *Total demand* on other subsystems reveals that it directly boosts *Production volume*, *Availability of CP&S*, and *de facto standardization*. Since these relationships are all part of a reinforcing feedback loop—specifically *P6(+)*, *CPS1(+)*, and *I1(+)*—an increase in *Total demand* drives the growth of these other systems. As these three variables in turn all in the long term increase the *Probability of purchase*, the *Total demand* ultimately also drives its own growth.

3.8.2. The Behavior of Production, Performance & Price

In §3.3 we noted that the price and production are part of the so called 'pig cycle' (*P2(-)* and *P3(-)*). This means that a higher *Price per unit* will lead to a higher *Production volume* and vice versa. This leads to the oscillation which is depicted in Figure 3.17.

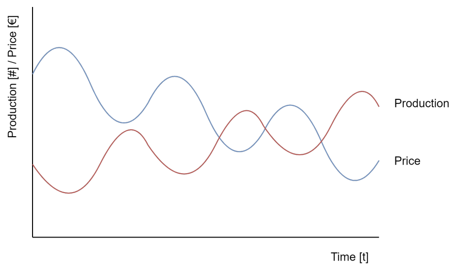

Figure 3.17: The oscillation of price and production

This figure also shows that the price over time lowers, while the production increases. The decrease in price is due to learning-by-doing (LBD), which centers around the relationship between *Production volume* and *Production cost*, and learning-by-searching (LBS), which is unified in *R&D investment*. LBD, together with the benefits of economies of scale, lowers the *Cost per unit* and is thus the most important motor in decreasing the *Price per unit*. LBS has the opposite effect by increasing the *Cost per unit* (*P4(+)*).

Since R&D primarily occurs during the development phase, this leads to a high initial price, which decreases as the need for R&D diminishes and the *Production cost per unit* falls. However, if one were to reinvest in R&D in later phases, this would cause the price to rise again. In this instance, it might be helpful to artificially increase the price upfront, as a higher price attracts more *R&D investment*.

This leads us to performance, because while *R&D investment* negatively affects the price, it enhances the technology's performance. Consequently, the impact of *R&D investment* on the *Probability of purchase* is also ambivalent. Therefore, it largely depends on the relative influence of price versus performance on this probability to determine whether investing in R&D is desirable.[15] However, these mechanisms do not explain the growth in *Production volume* over time. This is a result of *P1(+)*, which indicates that an increase in production raises the *Probability of purchase*, thereby generating greater demand for production.

These delays are typical of this subsystem. As a result, it may take considerable time for the feedback loops to raise production, performance, and price to the desired levels. A way to do so more effectively is by investing in a network.

3.8.3. The Behavior of Networks

A strong network has the possibility to increase the production and performance and thus also lower the price. An increase in *System resources* will consequently enhance the system. A downside of this in the beginning is however that these resources are mostly dependent on *R&D investment*, because the *Network resources R2(+)* need time to grow. Thus, a system with a weak network will need a high *Price per unit* to secure sufficient investment for growth (*N1(-)*).

Another way the network can be a motor in the system is by increasing *Legitimacy* through *Joint knowledge* and *Joint power/reputation*. However, feedback loop *I3(-)* shows that a high level of legitimacy can cause the network to stop investing in the system, as it believes that no further action is required. If the demand is at the level where the legitimacy has become implicit, it will further diffuse through the demand (*I1(+)*). Even so, the decline in investment in legitimacy will also influence the investment of the network in the production and performance of the technology. This might be problematic in a situation where the legitimacy is high, but where there is room for the development of the production and performance.[16]

3.8.4. The Behavior of Institutions

Therefore, we can conclude that *Total demand* is a motor (*I1(+)*) for legitimacy, through *Product standardization*. This is a more short term driver, but in the long term it can also be amplified by an increase in performance, production, *Governmental institutions*, and networks. These last two factors are especially interesting, because of their shared feedback loop *I2(+)*. The existence of this mechanism implies that any investment in the relationship between the government and the network can continuously keep strengthening the legitimacy.

Feedback loop *I3(-)* also plays a role here, as reduced investment in legitimacy by the network also affects

[15] Performance is influenced by both *Price per unit*, through *R&D investment*, and directly by *Production volume*. Both of these variables are known to oscillate. This leaves an interesting question for the one who translates the system into a Stock-Flow Diagram in order to simulate it. One could leave *Performance* as an oscillatory variable, or one could model it as a stock without an outflow that shows it as an accumulation of performance.

[16] In Chapter 4 we will see that markets have certain standards regarding prices, performance, and legitimacy. Thus, it is possible that an innovation cannot transition to a new market, because its high legitimacy led to an underdeveloped price and performance that is unacceptable for the new market.

the lobbying efforts for certain institutions, thereby reducing the number of *Governmental institutions*.

3.8.5. The Behavior of Complementary Products & Services

The role of *Availability of CP&S* in the system is primarily that of a helpful promoter of *Legitimacy* and *Probability of purchase* (*CPS1(+)*). Feedback loop *CPS2(+)* also shows that these complementarities can be created as a result of a strong network.

In the last few paragraphs, we explored the hypothetical behavior of the system to begin addressing the question: *What behavior do the individual elements display, and how does this behavior influence the behavior of other elements within the TIS?* Several key observations stand out. First, there are some critical drivers in the system, including *Total demand*, *Production volume*, *System resources*, and *Availability of CP&S*. Second, the success of an innovation ultimately causes its own downfall. Third, price and production tend to oscillate, with prices decreasing over time as production increases. Fourth, investment in R&D can have both positive and negative effects on the system. Finally, if legitimacy reaches a certain level, it will cause disinvestment in the network and institutions.

4

Transitions between Heterogeneous Markets

Until now, we have developed a model that shows how a TIS evolves in a single market. This emphasis on the existence of one market in which an innovation either fails or succeeds, is in line with how we historically think about the diffusion of innovations. Meaning that the lifecycle of an innovation consists of a development phase and a diffusion phase, and that the diffusion of the market takes place in one market in which all customers have similar needs and wants. However, Ortt's evolution model (2010) states that between these two phases, there is a third phase, the adaptation phase. In this phase, the TIS can enter niche markets where it gets the chance to develop and adapt itself before it enters the main market.[1]

A niche can be defined as "a small market consisting of an individual customer or a small group of customers with similar characteristics or needs" (Dalgic & Leeuw, 1994, p. 40). In this explanation of the theory, we limit these characteristics to the price/performance ratio of an innovation. Which results in the working definition of a niche market as a homogeneous market in which the customers have certain similar expectations of the price and performance of the innovation. The difference between a main market and a niche market is an arbitrary one. In general, a niche market is a smaller market which expects a higher price and a lower performance in exchange for e.g., novelty or specific functionalities. In contrast, a main market is the largest homogeneous market possible for this product, characterized by a demand for low prices and high performance. Successfully entering this market typically leads to the large-scale diffusion of a product.

Therefore, the lifecycle of an innovation from the time it enters the market in the adaptation phase to when it diffuses on a large scale consists of its entering a series of different markets (Dewald & Truffer, 2011).[2] Often starting out with niche markets in the adaptation phase and, if the innovation survives

[1] See also §1.1.

[2] The consideration of heterogeneous versus homogeneous markets stems from a fundamental debate on the nature of *homo economicus* within economics. Whereas neo-classical economics (NCE) regards actors as rational beings that compare all available information to be able to maximize their welfare, evolutionary economics (EE) believe agents to be boundedly rational. This means that instead of rationally evaluating all options, they follow routines. So, in NCE all actors are homogeneous, because they all have the same options, while in EE actors are heterogeneous, because they all follow different routines. These changes in

these markets, ending with entering a main market in the diffusion phase. It is the objective of this research to find out how the innovation transitions from the adaptation phase to the diffusion phase. To understand this transition, we have to understand the dynamics that guide both the changes in singular markets and the transitions between markets.

To do so, we will first immerse ourselves in the theory behind market transitions (§4.1). Then we will think about what this means for RNTI's (§4.2). In §4.3.1 we will examine this knowledge in the context of SDM which makes it possible to formulate a first answer to the following question.

> Which elements or interactions between elements within the TIS dictate whether an innovation progresses to the diffusion phase?

4.1. The Theory Behind Market Transitions

The success of an innovation in a market depends on two phenomena; how well the TIS changes to fit in with the characteristics of the market and how the market characteristics evolve to better accommodate the TIS. We encountered this problem earlier when looking at institutions. What we saw there is that the product becomes more and more standardized to gain legitimacy and thus appeal to more customers, while at the same time being subjected to sudden changes due to the flexible nature of demand.[3] This dynamic also exists for the TIS as a whole. Over time, the innovation becomes increasingly better adjusted to the market, by performing better, becoming cheaper, becoming more standardized et cetera. At the same time, the demand also conforms to the TIS, due to an increase in customers that buy the product and its complementarities and become tied to it due to sunk costs. This process of symbiosis between the technology and the market is also known as the locking-in of the technology (Tassey, 2000; Unruh, 2000).

This 'locking-in' eventually occurs in all markets, though it manifests differently depending on the characteristics of the locked-in TIS and its potential competitors.[4] However, we know from experience that despite this, all markets eventually always discard their preferred technology and adapt a new one. We have witnessed this over the past few hundred years, with the evolution of the cargo fleet from sailing ships to steamships, and now to container ships, but it is also prominent in the current energy transition from carbon-based technologies to clean alternatives (Geels, 2002; Unruh, 2000). The question that naturally follows this observation is: what are the conditions that tempt these locked-in markets to adapt a new product? These conditions have been studied by Geels (2006) and can be reduced to two main factors: changes within the TIS itself and changes in the external sociotechnical landscape.

4.1.1. Increased Price, Performance & Legitimacy

We know that a product becomes more attractive to a set of customers if it meets their expected price/performance ratio. We have stated that a niche market will accept a higher price and a lower performance, whilst a main market will only approve of a technology with a low price and a high performance. At first glance, it might seem strange that markets prefer a technology with a low performance. This can have several reasons, of which we will explain two. First, it is possible that the market has need of the specific new functionality that is provided by the technology, and it accepts the

routines are known as micro-evolutions (Geels, 2010).

[3] See also §3.5.1.

[4] For example, in some cases, multiple products become locked in simultaneously within the same market because their TISs are so similar that they are interchangeable, as with paperclips and staplers that rely on the same complementarities, networks, and institutions.

low performance of the product in exchange for this functionality. Secondly, the same product may have evolved to achieve higher performance in other markets, but in doing so, it may have lost certain features that are crucial in specific niches. As a result, these niches may continue to use an earlier version of the product. From this, one could conclude that the performance of a product is not absolute; it is made up of the performance of its individual components, whose importance differs between markets. In short, how well the performance of a product is regarded depends on the demands of the market. Thus, when we speak of a low performance, we mean that the product is in the early stages of development, and will know various other versions.

Over time price and performance can be developed in a series of niche markets, which set increasingly higher standards, before the final version of the product is developed that fits with the expectations of the customers in the main market. The TIS changes thus over time to appeal to ever larger markets. Additionally, there is another characteristic of the TIS that evolves over time and can be carried over to new markets: legitimacy. We have previously concluded that legitimacy is related to mass. The larger the group of people who view the innovation as legitimate, the faster it will gain legitimacy in the eyes of others.[5] This applies not only to single markets but also extends to the transition between markets. According to Johnson *et al.* (2006) the innovation first gains legitimacy in its current market by adhering to the expectations of this market. Once the innovation is validated locally, it is more likely to gain acceptance in other markets as well.[6] Therefore, over time, the innovation's legitimacy accumulates. In conclusion, one way for an innovation to transition from one market to the next is by lowering its price, and increasing its performance and legitimacy.[7]

4.1.2. Changes on the Demand-side

Another way for this transition to occur is for the preferences of the customers to change. This change can take place as a result of, for example, cultural or demographic changes, the emergence of a new type of technology which presents new possibilities, but also the occurrence of (natural) disasters which might change the needs of customers. All these situations might make locked-in technologies less attractive and create opportunities for new innovations to enter the market (Geels, 2006, 2010; Unruh, 2000). Geels (2006) calls these adjustments 'changes in the external sociotechnical landscape'. This indicates that the TIS is embedded in and informed by this broader system, while at the same time retaining its own dynamics. On a day-to-day basis, these dynamics between the building blocks determine the existence of the product within the market. However, in the long term, this existence is sometimes disturbed by changes in the surrounding landscape, after which the present technology is often replaced by a new innovation.[8]

[5] See also §3.5.2.

[6] In general, this statement holds true, which is why it forms the basis of this conceptualization of legitimacy. However, there are instances where a product's increased legitimacy in one market leads to decreased legitimacy in others. One example is videotelephony, which was initially embraced by the hearing-impaired community because, in contrast with regular telephones, it allowed them to lipread. Due to its adaptation in this particular market, the technology lost legitimacy in other markets, because of its image as an aid for the disabled (Ortt & Oppedijk van Veen, 1998).

[7] It is quite possible that other building blocks can also, to some extend, be transferred between markets. For instance, an existing network might facilitate the development of new networks in different markets. However, the success of this transfer largely depends on the market in question. Networks are only useful if they have relevant contacts in the new market. Complementary products and services can only benefit the new market if they are available in that area. Similarly, institutions are only applicable if the new market operates within the same legal framework. According to current findings, legitimacy is the only factor consistently proven to translate across different markets. For other building blocks, their transferability depends on the characteristics of the new markets. Therefore, when conducting a case study on a transition from one market to another using this SDM, researchers should consider for each building block if it can be transferred to other markets.

[8] In Geels' model (2006) the landscape functions as an external variable that is not linked to the building blocks within the TIS. However, it is likely that some links exist between these two entities. One could for example say that the same actors that determine the networks and institutions in the TIS also affect the broader socio-cultural landscape in which they likewise take

In conclusion, for an innovation to succeed in a market, both the TIS and the demands of the customers, as informed by the external landscape, have to line up. As a result, a transition can occur in one of three ways: when the TIS changes to appeal to new markets, when the demands from the market change to accommodate a new TIS, or when both of these changes happen simultaneously.

4.1.3. Transition Scenarios

These three scenarios and a base case are presented in Figures 4.1 and 4.2. All scenarios consist of two different markets that exist at a certain point in time. At that time, these markets only adopt technologies whose price, performance, and legitimacy fall within a range they find acceptable. As an illustration, if the lowest possible price for this type of product is 10 EUR (0) and the highest is 20 EUR (1), the customers in market 2 under scenario 1 would be willing to pay between 12 and 15 EUR. The line reflects the price, performance, and legitimacy of the innovation in question at that time.

The base case (scenario 1) already demonstrates that a technology might be accepted in one market but not in another, because not all preferences of that market correspond with the characteristics of the technology. In this scenario, neither the price nor the legitimacy align in the second market. Scenario 2 shows what happens when the characteristics of the TIS change; due to a lowered price and more legitimacy, the technology fits in with the second market. However, these changes also make the product less appealing to the first market. As a result, it is likely to be replaced by another product. In scenario 3 the demands of the second market change, due to a change in the landscape, which leads to the acceptance of the technology. Lastly, in the fourth scenario, both the preferences of market 2 and the characteristics of the TIS change to align.

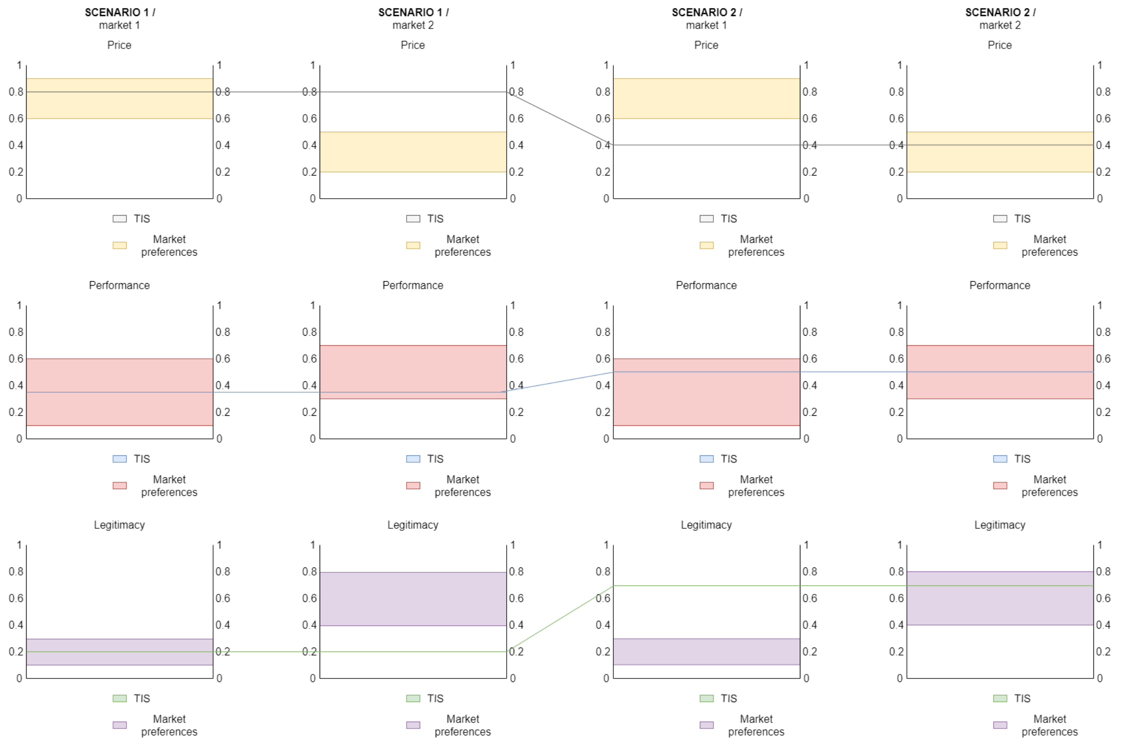

Figure 4.1: Scenario 1 & 2

part. It is outside of the scope of this SDM to model other relations between the landscape and the TIS apart from the link between *Total demand* and *Demand flexibility*. However, the possible dynamics between the landscape and the TIS might be an important part of the system that is worth consideration in future models.

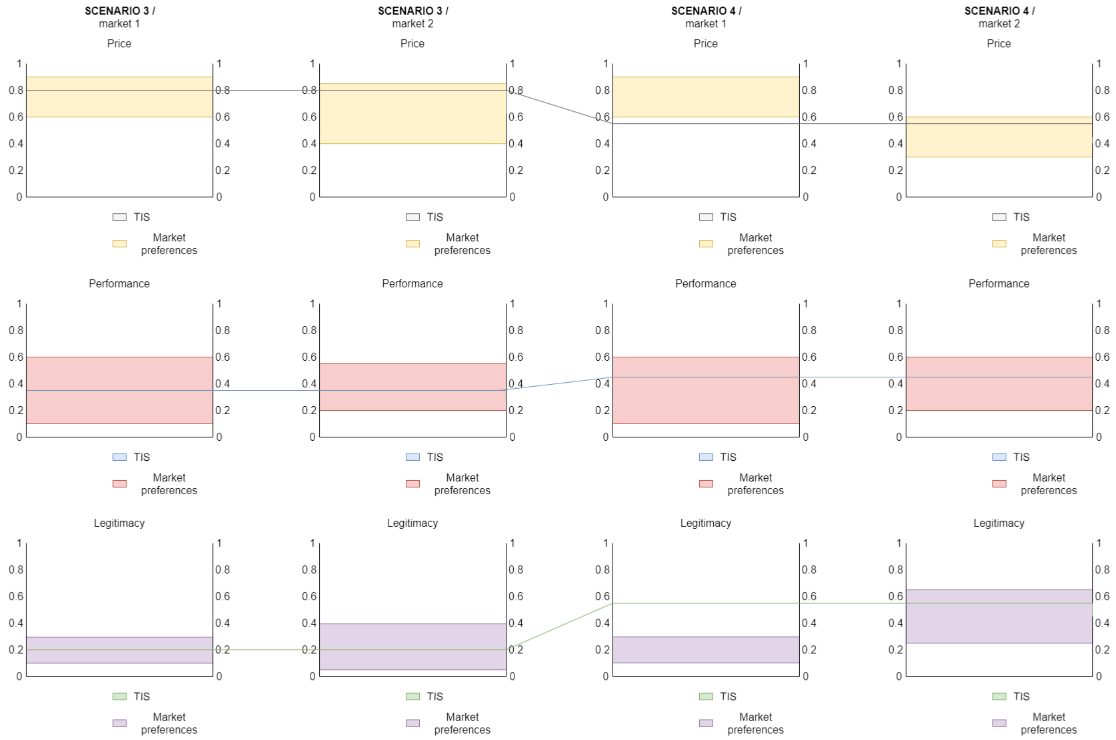

Figure 4.2: Scenario 3 & 4

4.2. Transitions of Radically New Technological Innovations

In Chapter 1 Introduction, we learned that RNTIs are technologies that are radical due to their excellent performance/price ratio or because of their new functionalities (Jacobsson & Bergek, 2011). These properties make them potentially highly useful; nevertheless, they often do not last long enough to become established in larger markets. The reason for this failure is that their TIS is often not sufficiently developed to compete with other existing products. They often lack legitimacy, complementary products and services, and a sufficient network (Olleros, 1986). Therefore, to enter a (new) market, these building blocks must be developed to a level where their attributes align with the demands of the market. This development can only take place inside a market. It is therefore essential that an RNTI can enter a market that accepts its underdevelopment and allows the TIS time to grow.

This market can be a result of two different processes. It can be a niche market that is willing to accept the underdevelopment of the TIS in exchange for novelty of the RNTI, as was the case with Tesla, where early adopters embraced the technology despite its initial shortcomings.[9] Alternatively, the novel applications of the RNTI might induce a shift in demand-side preferences, as illustrated in scenario 3 in Figure 4.2, leading to the technology's adaptation (Geels, 2006).

In summary, in the short term, RNTIs rely on niche markets for the time to develop their TIS. In the long term, their excellence may lead to changes in the external landscape, which might result in broader market adoption.

[9] See also §1.1.

4.3. The System Dynamic Modeling of Market Transitions

In the preceding paragraphs, we developed a theory outlining the conditions under which RNTIs can successfully enter new markets. From this theory we have derived four important insights that will play a fundamental role in the design of the simulation model.

4.3.1. Dynamic Models of Previous Insights

First, in single markets, there exists a dynamic between the demand- and the supply-side which over time leads to a lock-in of the technology. This is a result of two linked processes. First, this stems from the process of standardization which naturally occurs within the TIS.[10] This standardization leads to an increase in probability of purchase, which in turn leads to a growth in *Total demand*. This *Total demand* results in a decrease of the *Demand flexibility* which subsequently results in an increase of *Probability of purchase*.[11] This dynamic can be seen in Figure 4.3.

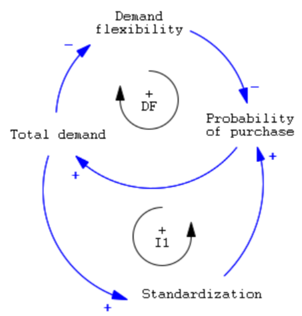

Figure 4.3: Standardization & demand flexibility

This simultaneous increase of standardization and decrease of demand flexibility leads to a lock-in of technology, which is visualized in Figure 4.4.[12] This graph shows that when the *Probability of purchase* for the product is low, which means that the market is open to various technologies and their characteristics, almost any price is acceptable. However, as this dynamic takes effect, the *Probability of purchase* of the technology in the market increases. This means that, over time, the preference for this product and its price becomes so dominant that other technologies cannot compete. At that point the technology in the market becomes locked-in and other competing technologies become locked-out.

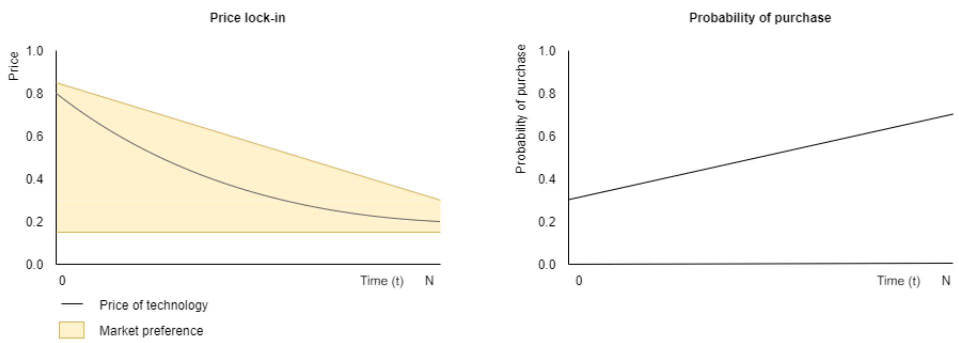

Figure 4.4: Price lock-in

[10] Also see §3.5.1.
[11] For an explanation of these variables, see Table 3.1 and §3.5.1.
[12] In this example, only price plays a role. However, in the SDM, the other building blocks also influence the process of standardization.

Our second insight was that products can transition to other markets if their characteristics are in line with the characteristics expected by the market. For each transition, fundamentally, only the values associated with price, performance, and legitimacy can be transferred to a new market. These transitions are illustrated in Figure 4.5, whereby the green lines represent the transition of these values from the first to the second market (M2).[13]

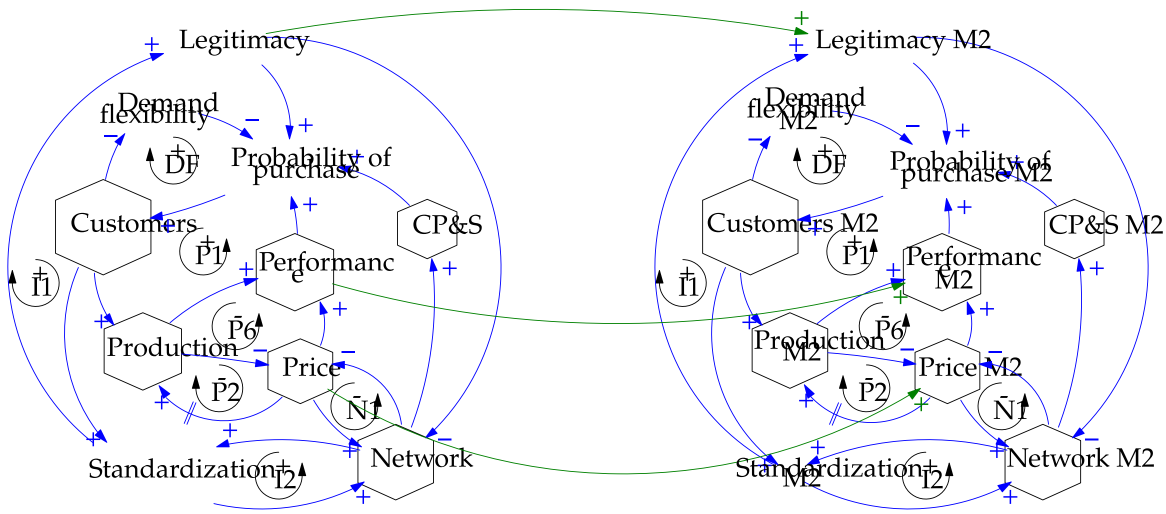

Figure 4.5: Transition through the development of the TIS

Thirdly, Geels (2006) showed us that a transition can also be facilitated by a change in the external landscape. In this case, the shift in demand preferences moves the customers away from the locked-in technology and makes them receptive to alternative technologies. In the model, this is represented by a new link between *External landscape* and *Demand flexibility*. Whereby a change in the landscape can cause a highly inflexible demand to become flexible once more. This change is visualized in Figure 4.6. The Figure shows that, like in Figure 4.4, a change in market preferences leads to a change in *Probability of purchase*. In this case, the external influence from the landscape leads to a decrease in the *Probability of purchase* for the product in the market, thereby giving other technologies the opportunity to replace it. In conclusion, a change in the external landscape can lock-out a previously preferred technology and widen the market to allow new technologies to start the process of becoming locked-in.

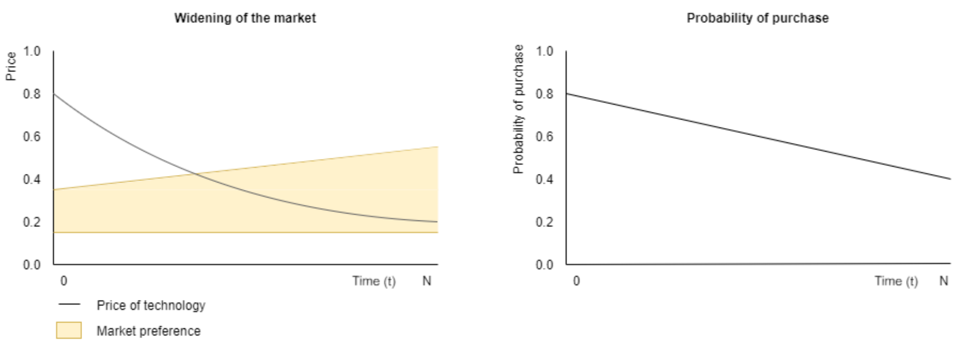

Figure 4.6: Market widening

[13]The markets in Figure 4.5 are highly simplified versions of the model of the TIS as shown in Figure 6.2.

Our fourth insight relates to RNTIs. The theory showed us that these innovations lack legitimacy, complementary products and services, and a network when they first enter the market and that it needs a market to develop these building blocks. This means that when we model the first market the RNTIs enter, the value of *Legitimacy*, *Availability CP&S*, and *System resources* in the model will be low, whilst the value of *Demand flexibility* will be high, resulting in a low *Probability of purchase* for the previous product in that market and a high *Probability of purchase* for the RNTI.[14]

4.3.2. How Transitions Succeed or Fail in the System Dynamic Model

These four insights tell us how a technology can become locked-in, how a market can become receptive to a new technology, and what a RNTI needs in order to develop. However, we still do not know how the actual transition occurs in the SDM. To understand this, we have to more precisely define the variables *Demand flexibility*, *Total demand*, *External landscape*, and *Probability of purchase* and their relationships.

For this, we will start with one of the central variables in our model: *Probability of purchase*. In §3.2, following Milling & Maier (2020), we decided to use *Probability of purchase* as an aggregated variable, combining all variables within the TIS, or supply-side, before they could impact the demand-side. When we started to build the SDM, we found out that *Probability of purchase* is not only influenced by the supply-side, but also by the demand-side, through *Demand flexibility*. This raises the question of how much influence these variables have, in relation to one another, when contributing to the *Probability of purchase*. We will start with the influence from the demand-side.

The demand-side, which is united in *Demand flexibility*, is influenced by *Total demand* and *External landscape*. While *Total demand* has been made clear, *External landscape* as of yet only consists of a theory. We know that it represents a long term change in the preferences of customers, which is informed by various factors, such as cultural changes or (natural) disasters. We will represent this change by modeling *External landscape* as an oscillating graph, similar to Figure 6.3, which illustrates how customer preferences for the technology change over time. The fact that the change in demand preference is modelled as a fluctuating graph instead of, for example, linear regression, makes it possible for *External landscape*, to have both a positive and a negative influence on the *Demand flexibility*. At times when the external landscape is positive, it will increase the *Demand flexibility*, which means that the market demands have changed in favor of a new product. In contrast, when the *External landscape* is negative, it decreases the *Demand flexibility*, meaning that the demand wants to hold on to the current technology in the market. This is also depicted in Figure 6.3.

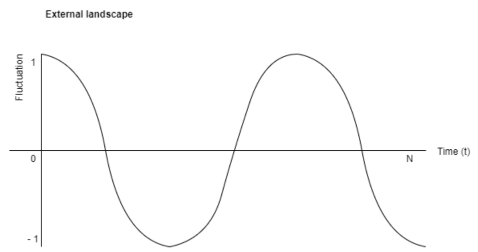

Figure 4.7: Fluctuation of the external landscape

[14]For an explanation of these variables and their interactions, see Table 3.1 and Figure 6.2.

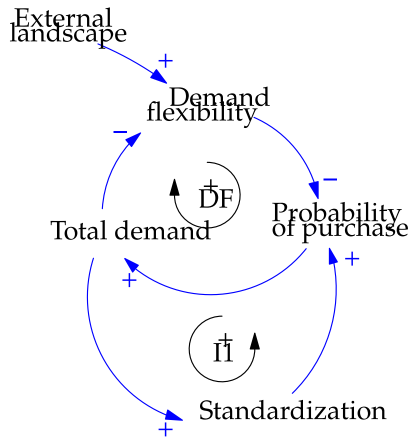

Figure 4.8: CLD including the external landscape

Figure 6.3 also shows that the *External landscape* has the power to either positively or negatively reinforce the feedback loop (*DF(+)*). When the landscape is negative, indicating low flexibility and a desire to maintain current technology, the *Probability of purchase* for the technology increases. This creates positive reinforcement within the feedback loop, leading to continuous growth in *Total demand* as long as the *External landscape* remains negative. Conversely, a positive *External landscape*, characterized by a strong desire for change, results in a decrease in *Probability of purchase*. This negative feedback loop causes *Total demand* to continuously decline while the *External landscape* remains positive.

The demand-side influences the *Probability of purchase* through this continuous switching between a positive and a negative reinforcement. The supply-side, on the other hand, is expected to have consistently positive influence on the *Probability of purchase*. As long as there are customers willing to buy the product, the building blocks will keep developing, all the while making the TIS more attractive to new customers.

How the market is opened up for transitions depends on the relative influence of the demand-side and supply-side on the *Probability of purchase*. Which of the two has the upper hand depends on the market. If the *Probability of purchase* is for 100% determined by the *Demand flexibility*, the willingness to buy a product only depends on the external preference of the customers. In the long term, this results in a highly volatile market. If the market is inflexible, it will adopt the TIS regardless of its characteristics. However, when the market inevitably turns flexible again, it will cold-heartedly switch to another technology, irrespective of the growth the TIS experienced while the market was favorable towards the technology. This inclination towards change makes these markets niche markets. These characteristics make these demand-focused markets good entry markets for RNTIs. Firstly, because they do not require the TIS to be developed in order to diffuse. Secondly, because the demand-induced high *Probability of purchase* leads to the generation of customers that are needed by the TIS in order to develop its building blocks.

Once the TIS is developed, it can also enter supply-oriented markets. In these markets the *Probability of purchase* is fully depended on the quality of the TIS. Which means that the technology will succeed if it has enough system resources, a low price, high legitimacy, a high performance et cetera, and it will fail if it lacks these attributes. These are the markets a RNTI can only enter if it had time to develop its price, performance, and legitimacy in another market. However, these are also most likely the larger and thus more profitable markets, because they rely more on the quality of the technology. We previously called these markets 'main markets'.

In this example, the *Probability of purchase* is either 100% determined by the demand- or by the supply-side. However, it is likely that the *Probability of purchase* of most markets will be a mix of both.[15]

Having established how RNTIs can successfully enter new markets, we also want to understand how they might fail to do so. In the case of a demand-oriented market, the answer is quite obvious. Namely, that a technology will fail if it does not satisfy the external preference of the customers. Alternatively, if the supply-side has the overhand, the failure is a result of a lack of customers. In this case, due to an underdeveloped TIS, the low *Probability of purchase* will not generate enough demand to instigate a proper development of the TIS. Although the SDM will probably still indicate that the technology will eventually diffuse, the process would be so slow that it would be unsustainable for the companies developing and selling the technology.

4.4. Assumptions

1. Only the variables *Price*, *Performance* and *Legitimacy* can be transferred across markets.
2. A niche is defined by the fact that it accepts a higher price and a lower performance. The specific values of these variables differ across niches.
3. A main market always strives for a low price and a high performance.
4. Over time, the legitimacy always accumulates, the price always lowers and the performance always increases.
5. Transitions between markets can only occur in three ways: when the TIS changes to appeal to new markets, when the demands from the market change to accommodate a new TIS, or when both of these changes happen simultaneously.
6. All TISs will lock-in in their market and will ultimately be locked out again.
7. Assuming that any existing demand is always met by the supply-side and the demand is in favor of the technology, over time, all TISs will diffuse in all markets.
8. When we refer to the adaptation of a TIS across different markets, we are specifically talking about the adaptation of a single functionality and its TIS. If, for example, the development of a production system leads to the emergence of an entirely new functionality, this would be treated as a separate functionality with its own distinct phases.

4.5. Conclusion

At the start of this chapter, we determined that the existence of an adaptation phase indicates the existence of heterogeneous markets. These markets are each defined by varying demands for price and performance, typically ranging from high price and low performance in niches to low price and high performance in main markets. We also saw that within the individual markets, the demand and the TIS tend to exist in symbiosis, which in time creates a lock-in of the technology. However, after a

[15] If we compare these transitions to the scenarios previously formulated in Figures 4.1 and 4.2 we could conclude that scenario 2 represents a transition into a supply-side market, scenario 3 shows a transition into a demand-side market and scenario 4 illustrates a transition into a market that is a mix of both.

while, this technology will itself inevitably become locked-out. This lock-out can happen in two ways: either a new TIS better meets the demands for price, performance, and legitimacy compared to the now locked-out technology, or the demand shifts, making a different product a better fit. If we view this from the perspective of a TIS trying to enter a market, we could say that this is possible in three kinds of scenarios. First, the TIS changes to better fit the demands of the market. Secondly, the demand changes to include the TIS and thirdly, both the market and the demand change to better align with each other.

If we were to model this transition between markets using an SDM, we could say that the *Probability of purchase* is influenced by both the demand and the TIS. In this model, demand is represented as an oscillating graph, reflecting shifts caused by changes in the external landscape. Different scenarios can be illustrated by the relative impact of demand or TIS on the *Probability of purchase*. In niche markets, demand typically dominates, leading to volatility, but also, at the right time, creating a helpful environment for emerging RNTIs. In main markets, on the other hand, the TIS is more prominent, which results in steadier markets that cannot be conquered easily by other products.

This research into how the TIS can transition into a market also partly answers sub-question 5: Which elements or interactions between elements within the TIS dictate whether an innovation progresses to the diffusion phase?

5

A Simulation Model of Market Transitions

One of the central themes of this thesis is the dynamic between flexibility and standardization. This topic was initially introduced through the work of Ortt & Egyedi (2014), who highlight a debate among researchers regarding the role of regulation in the introduction of innovations. Although regulation can cultivate economies of scale, it can also limit product variety and, as a result, constrain innovation (Blind, 2004; Swann, 2000; Temple et al., 2005; Wölker, 1996).

In §3.5.1 we contemplated this discussion from a System Dynamics perspective. There we observed that this interplay between standardization and flexibility is a fundamental dynamic in the system. When a product is subjected to standardization, it evolves over time from a functionality that can be translated into various designs to a single dominant design. This dominant design is reinforced by market mechanisms, networks, and governmental institutions, which builds trust and in turn leads to more customers. At the same time, the flexibility of the market in which the product exists allows for sudden shifts in customer preference, which is driven by external factors, toward a different version of the product, resulting in a collapse of demand for the product. Such shifts may leave a company vulnerable if it has already invested heavily in the dominant design.

In Chapter 4 we considered this dynamic in the context of market transitions. There we concluded that there are three ways for a product to enter a new market; by having better properties than the current dominant design in the market, by entering at a time when the market preference has just shifted, or through a combination of both. We then made some first steps in specifying this dynamic in order to better understand it and its role in market transitions. This resulted in a graphical definition of the variable *External landscape* and a new Causal Loop Diagram which shows the variables and relations that make up this dynamic, as shown in Figure 6.3.[1]

These previous insights have helped us answer many of our sub-questions. However, one remains: "How does the number of customers in the TIS change over time?" Or; how does the system behave as

[1]See also §4.3.2 and specifically Figure 4.7.

measured in the change in customers? To answer this question, we have to go beyond economic theory and System Dynamic thinking and enter the world of mathematical modeling. This allows us to go further than the behavior hypotheses as we have formulated them in §3.8 and §4.3.2 and to see how all these behaviors influence each other to form a singular graph displaying the change in the number of customers.

Since simulating the complete system depicted in Figure 3.15 is beyond the scope of this study, our focus will be on the dynamic interplay between standardization and flexibility, and its impact on *Total demand*. This focus is motivated by two reasons: first, this important dynamic could play an important role in answering our research question; and second, this exercise will assist us in understanding how to translate a Causal Loop Diagram grounded in economic theory into a robust mathematical model.

To properly develop and utilize a simulation model, several steps must be followed, which are outlined in the following paragraphs. §5.1 focuses on the construction of the model, which is verified and validated in §5.3. The model is then experimented on in §5.4, the results of which can be found in §5.5. This is followed by a conclusion in §5.6.

The model was constructed and simulated using Vensim by Ventana Systems, and the data analysis was performed in Python with JupyterLab. An explanation of the shapes used in the diagrams can be found in Appendix A.

5.1. Model Conceptualization

The aim of this model is to present a mathematical translation of the CLD on flexibility and standardization, as illustrated in Figure 6.3. To achieve this, four decisions need to be made: identifying the stocks and flows, defining the equations, determining the units, and ensuring the model is balanced. This paragraph will outline these decisions and conclude with a list of assumptions that form the basis of this translation.

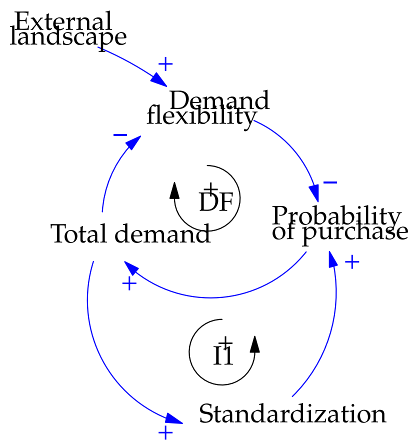

Figure 5.1: CLD including the external landscape

5.1.1. Stocks and Flows

In *Industrial Dynamics* Jay Forrester beautifully explains the difference between a stock and a flow, which he calls a level and a rate: "A good test to determine whether a variable is a level [stock] or a rate [flow] is to consider whether or not the variable would continue to exist and have meaning in a system that has been brought to rest. If all activity, in the form of flows, were to cease, the levels [stocks] would still exist. Stopping the receiving and shipping of goods does not affect the continued existence of inventory that is in the warehouse. If all activity in a system is momentarily stopped, rates [flows] are unobservable. There is no movement to be detected, but the levels [stocks] continue to exist. The levels of physical quantities such as goods, money, and personnel would be countable in the stationary system." (Forrester, 1961, p. 68). In conclusion, stocks represent accumulations within the system, whilst flows depict the changes in the system that feed this accumulation.

If the system as described in Figure 6.3 would be stopped, three variables would continue to exist: *Demand flexibility*, *Standardization*, and *Total demand*. In that case, the value of *Demand flexibility* would represent how much the customers prefer the innovation, the value of *Standardization* would be the level of acceptance for the innovation as the standard, and the *Total demand* would show the number of customers that have bought the product at that point in time. On the other hand, *Probability of purchase* is a piece of information that lets *Total demand* know what the levels of *Standardization* and *Demand flexibility* are, so it can adjust its own level accordingly. It is lost once the system stops changing, and it is therefor a flow. Finally, *External landscape* is a factor that influences the change in *Dynamic flexibility*. It is therefore part of this flow equation, along with *Total demand*. However, to maintain an overview of all components in the model, we depict it as an influence on the flow, making it an auxiliary variable (Forrester, 1961). These four variables are all part of the Stock-Flow Diagram in Figure 5.2. This diagram shows many more variables, most of which are auxiliaries, that will be addressed in §5.1.2. Here it is important to mention two new flows. First, the *External demand change*, which informs the *Demand flexibility* and secondly, the *Change in standardization*, which informs the *Standardization*.

One might also notice that none of the stocks have outflows. For *Total demand* this speaks for itself since it registers how many persons have bought the product, which cannot be reversed. For *Standardization* this is based on an assumption. Namely, that the amount of legitimacy for a product, which is closely related to standardization in Figure 3.15, is equal to the number of customers.[2] As a result, if one has bought the product, one automatically adds to its legitimization. Lastly, regarding *Demand flexibility*, this is related to sunk costs. Once people have purchased the product during a period of high preference, they are likely to maintain their preference because they do not want to lose their investment.[3]

[2]See also Figure 3.12.
[3]See also §4.1.

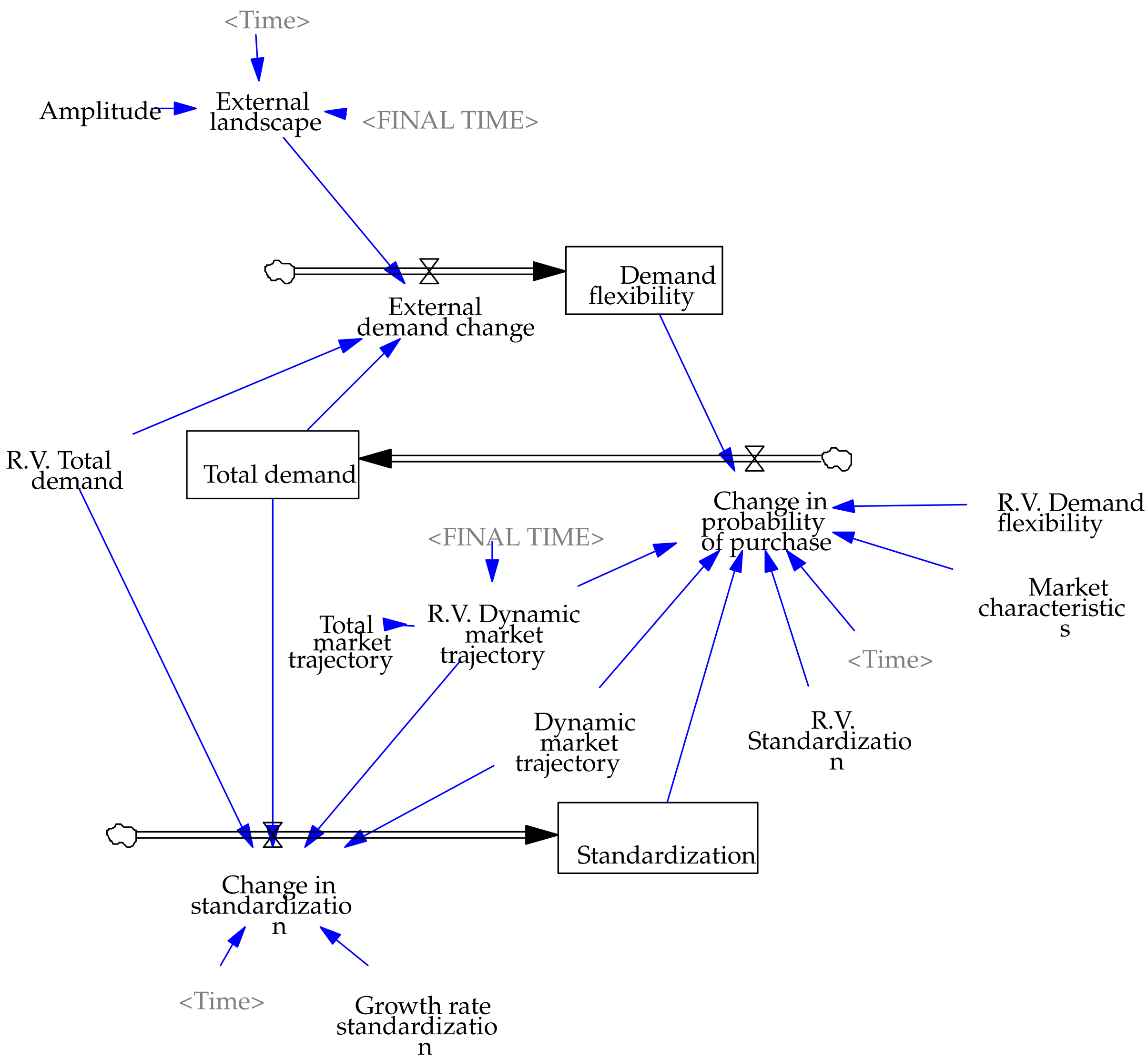

Figure 5.2: Stock-Flow Diagram

5.1.2. Equations and Units

As a stock represents an accumulation, it is expressed as an integral of the incoming flow at a point in time, as shown in Equations 5.1, 5.2, and 5.3, whereby Time = t and Final time = T. The equation for *Total demand* also includes an intial value, namely 0.01, because this stock acts as a multiplier in both the flow *Change in standardization* and *External demand change*. Thus, if the initial value was to be zero, the system would immediately stabilize at zero. The value of 0.01 was chosen because it is larger than 0, but small enough not to affect the results. As this value activates the system, initial values for other stocks are unnecessary.

$$Total\,demand(t) = 0.01 + \int_{t=0}^{T} Change\,in\,probability\,of\,purchase(t)\,dt \tag{5.1}$$

$$Demand\,flexibility(t) = \int_{t=0}^{T} External\,demand\,change(t)\,dt \tag{5.2}$$

$$Standardization(t) = \int_{t=0}^{T} Change\ in\ standardization(t)\,dt \tag{5.3}$$

The first flow is *Change in standardization*. This variable is determined by Equation 5.4, which consists of three parts. First, the *Dynamic market trajectory(t)*. This is a lookup, see Figure 5.3, which represents the change in the number of new customers over time. The shape of this graph is based on a similar graph by Milling & Maier (2020).[4] We have concluded earlier that standardization is closely related to legitimacy and that legitimacy is equal to the number of persons who have bought the innovation. As a result, the trajectory of the change in customers also determines legitimacy and thus informs the change in standardization. Secondly, similar to the CLD shown in Figure 6.3, this flow is determined by the *Total demand*. Lastly, it is also influenced by *Growth rate standardization*. This variable is a highly simplified representation of how the development of all other building blocks impacts the process of standardization, as illustrated in Figure 6.2. The average growth rate is 1, but an underdeveloped TIS will have a lower rate, thus slowing the growth of *Standardization*, and vice versa.

Equation 5.3 also indicates that both *Dynamic market trajectory* and *Total demand* are divided by a reference value (R.V.). The reference value is typically the average of the variable, which makes it possible to divide two variables that have the same unit, thus obtaining a normalized input for our model (Sterman, 2000). This is crucial because the level of abstraction requires the model to be dimensionless.[5] The use of a reference value is unnecessary for multipliers like *Growth rate standardization*, because they are already unitless.

$$Change\ in\ standardization = Growth\ rate\ standardization \cdot \frac{Dynamic\ market\ trajectory(t)}{R.V.\,Dynamic\ market\ trajectory} \cdot \frac{Total\ demand}{R.V.\,Total\ demand} \tag{5.4}$$

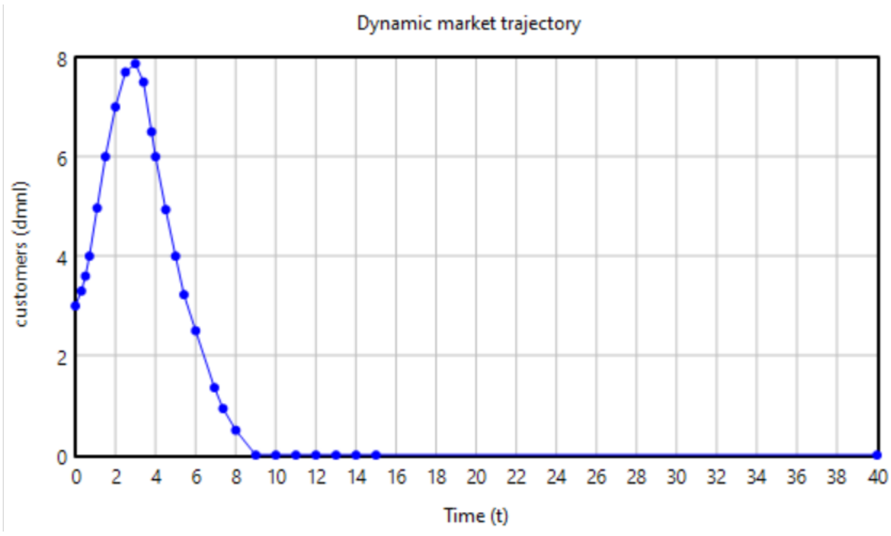

Figure 5.3: Lookup Dynamic market trajectory

The second flow is *External demand change*. This variable determines how the preference of the customers for the product changes. Equation 5.5 indicates that it is largely determined by *External landscape*. This

[4] See also §3.8, §3.2, and particularly Figure 3.3.
[5] See also §3.7.

function creates an oscillating graph, that when positive will increase the demand flexibility, thus creating room for the new innovation.[6] When it is negative, the MAX function guarantees that the stock value does not fall below zero. This allows the stock to continue representing the customers who retain their preference due to sunk costs, even when the external landscape turns negative. The Equation also shows the relation between *Total demand* and *Demand flexibility* which is derived from Figure 6.3. To normalize this variable, it is divided by its reference value.

$$External\,demand\,change = MAX(External\,landscape \cdot \frac{Total\,demand}{R.V.Total\,demand}, 0) \tag{5.5}$$

The formula for *External landscape*, Equation 5.5, is a standard sine function, based on Figure 4.7, that is made up of an *Amplitude*, which will play a role in the balancing of the system, and a final time (T) to ensure that the *External demand change* displays both a positive and a negative phase during the run time, to show the influence of both phases on the behavior of the system.

$$External\,landscape = Amplitude \cdot \sin(\frac{2\pi}{T} * t) \tag{5.6}$$

The last flow, *Change in probability of purchase*, plays a central role in the system as it brings all the stocks together This is evident in Equation 5.7, which demonstrates how *Standardization* and *Demand flexibility* ultimately impact the *Total demand*. Before this influence occurs, the stocks are multiplied by a variable called *Market characteristics*, which represents the relative effect of these stocks. In the base case, it is set to 0.50, ensuring that both stocks have equal influence and together sum to 1. This second part of the equation serves as a multiplier for *Dynamic market trajectory*, whose shape shows the trajectory of change in the number of customers over time.

$$\begin{aligned} Change\,in\,probability\,of\,purchase = {} & \frac{Dynamic\,market\,trajectory}{R.V.Dynamic\,market\,trajectory} \cdot \\ & (\frac{Standardization}{R.V.Standardization} \cdot Market\,characteristics + \\ & \frac{Demand\,flexibility}{R.V.Demand\,flexibility} \cdot (1 - Market\,characteristics)) \end{aligned} \tag{5.7}$$

5.1.3. Balancing the Simulation Model

The equations show that all stocks and the *Dynamic market trajectory* are divided by reference values in order to make them dimensionless. These reference values are typically the average of the variable to produce a normalized output, where a value of 1 indicates that the current value is equal to the average (Sterman, 2000). In this simulation model, this is true for the *Dynamic market trajectory*, whose reference value is the sum of the values in the stock divided by the runtime. In the case of the other reference values, this is a bit more complicated because the values of their corresponding variable fluctuate as the system changes. One can therefor not use the sum of the stock in one run, but one has to combine all possible values for all possible runs and average over those. This process is more complicated and time consuming than this study allows for.

[6] See also §4.3.2 and Figure 4.7.

To simplify, we employed a shortcut based on the goal of making all stocks equally influential in the system, with their values falling within a similar range. When we ran the model, we found that *Standardization* and *Total demand* were, on average, twice as large as *Demand flexibility*. Consequently, their reference values were set to 2, while the reference value for *Demand flexibility* remained 1. This adjustment brought the values closer to the same range. However, there was still a significant difference that resulted in a greater influence of *Standardization* on the inflow *Change in probability of purchase* compared to *Demand flexibility*. This inequality would detract from the usefulness of the variable *Market characteristic*, as even if its value was 0.50, the impact of *Standardization* would still exceed that of *Demand flexibility*. To address this issue, we adjusted the *Amplitude* of the sine function for the *External landscape*. It was found that setting this value to 1.25 allowed both *Standardization* and *Demand flexibility* to stabilize at a value of 8.4, thus ensuring they had approximately equal influence on the inflow of *Total demand*. Thus configuring the reference values and the amplitude balanced out the model enough to make it fit for purpose.

5.2. Assumptions

1. There are no outflows in the model.
   (a) Buying a product cannot be reversed.
   (b) *Standardization* has the same trajectory as legitimacy, whereby legitimacy is an accumulation of the persons who have bought and therefore legitimized the product.
   (c) The stock *Demand flexibility* cannot be negative, in order to keep representing sunk costs. As a result, we also assume that sunk costs play an important role in the system, which in reality may differ depending on the substitutability of the product.
2. The graph, see Figure 3.3, made by Milling & Maier (2020) is an average representation of the change in customers for an innovation over time.
3. The changes in the external landscape can be simplified to be represented by a sine function.
4. The evolution of the building blocks can be simplified to a growth rate that affects the standardization process.
5. The model can be made fit for purpose by balancing out the reference values and the *Amplitude*.

5.3. Verification & Validation

In order to ensure that the model is fit for purpose, it must be verified and validated.

5.3.1. Verification

The verification of the model comprises two parts: an explanation of the chosen numerical method and a decision on the time step. The numerical method used is Euler, because a first order derivative is discontinuous due to the MAX function in Equation 5.5 (Auping et al., 2023).

The time step in the model is set to 0.001. This value was selected after testing various time steps and seeing their effect on the *Total demand*. Figure 5.4 shows that time steps 0.001 and 0.0005 overlap. To gain accurate results with minimal runtime, time step 0.001 was selected (Auping et al., 2023). In general the time step is $\frac{1}{2}$ to $\frac{1}{10}$ of the smallest delay time, which is in this case one year. Here, the time step is $\frac{1}{100}$ of this delay, which is likely due to the more frequent changes in the lookup and sine functions.

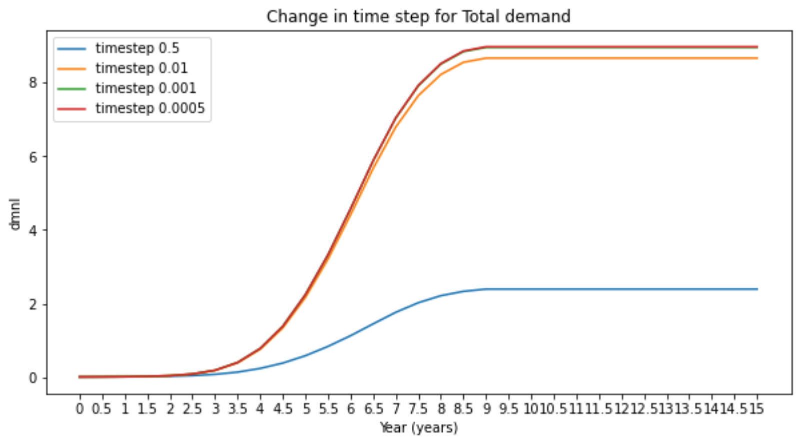

Figure 5.4: Experimentation with timestep

Based on these choices, we can conclude that there are no numerical errors in the model.

5.3.2. Validation

Next, we want to know if the behavior of the model corresponds to that of the real system. Thus, we conduct three tests: face validation, sensitivity analysis, and extreme conditions testing.

The face validation was carried out by two TU Delft teachers who specialize in SD-modeling. They concluded that the structure of the model is valid. However, they mentioned that the names of the stocks *Total demand* and *Demand flexibility* imply that they are rates that change a stock rather than being stocks themselves. In the case of *Total demand* this choice originated from a study by Milling & Maier (2020), who also have a variable called *demand*, which is an accumulation of *imitative demand* and *innovative demand*, and although I had the insight to change imitative and innovative demand to purchases, I refrained from doing so in the case of *Total demand*. In a new version, the name of the stock should therefore be changed to *Total purchases*. In the case of *Demand flexibility*, its meaning changes when translating it to a simulation model. In the CLD its function is to show how the preference of the demand changes, whilst in the model it exists to show the current level of preference for the product by the demand. In the model, it should therefore be called *Demand preference*. Interestingly, this reveals something about the SDM method itself. It is often assumed that a CLD can be directly converted into a simulation model. However, this process shows that translating to a simulation model can alter the interpretation of the variables. The face validation also revealed a structural uncertainty in the model. Equation 5.7 shows that the rates of standardization and demand flexibility are added because it seems logical that together they should add up to one. However, it is also possible that multiplying will give more realistic results in some scenarios. This is further explored in §5.5.2.

For the second test, we aim to see the model's sensitivity to variations in the data. This was tested by increasing and decreasing all constants by 10% and letting Vensim run 200 experiments with values sampled between these minimum and maximum values. This created the graph in Figure 5.5.[7]

[7] For the sensitivity analysis of *Standardization* and *Demand flexibility*, see Appendix B.

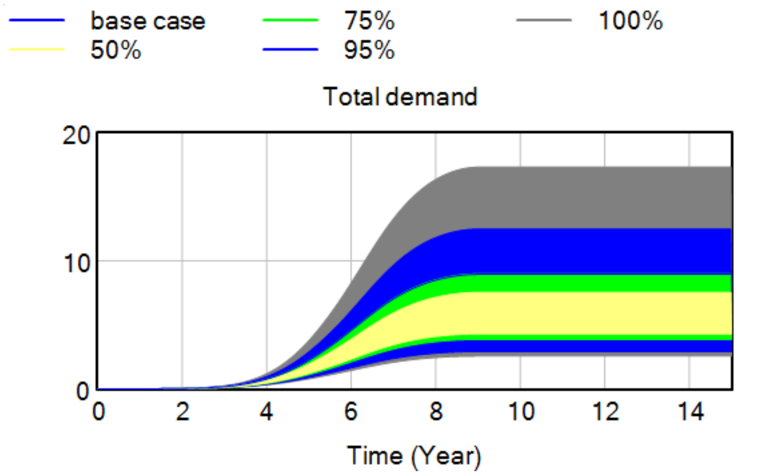

Figure 5.5: Sensitivity Total demand

The Figure shows that although the model is numerically sensitive, meaning that the numerical value of the variable is sensitive to change, it is not behaviorally sensitive (Auping et al., 2023). Although the S-curve has different values, it is still an S-curve. As this model, due to lack of data, is based on trajectories, the only important thing is that these trajectories are not sensitive in behavior. As the values in the model have no meaning anyway, its sensitivity is of no importance to us.

For the extreme conditions test, we changed the number of fluctuations in the *External landscape* from one to ten. This suggests that, rather than experiencing a major shift in the landscape every 15 years, such changes would occur every 1.5 years. The subsequent changes in the model are shown in Figure 5.6. The graphs show that the shape of the behavior stays the same, but that it diffuses on a far lower level. This phenomenon can be attributed to the fact that in the base case, demand consistently favors this technology as standardization increases. Only after the product has reached a certain level of standardization does the preference shift. By that time, the product has already been purchased numerous times. In this scenario, the preference continues to shift whilst the standardization grows. Consequently, there are periods when demand flexibility does not contribute to the growth of total demand. This ultimately leads to a decrease in overall demand. This behavior corresponds with reality, where the accumulation of purchases also depends on the moments of preference for the product. The behavior generated under extreme conditions is therefore still realistic.

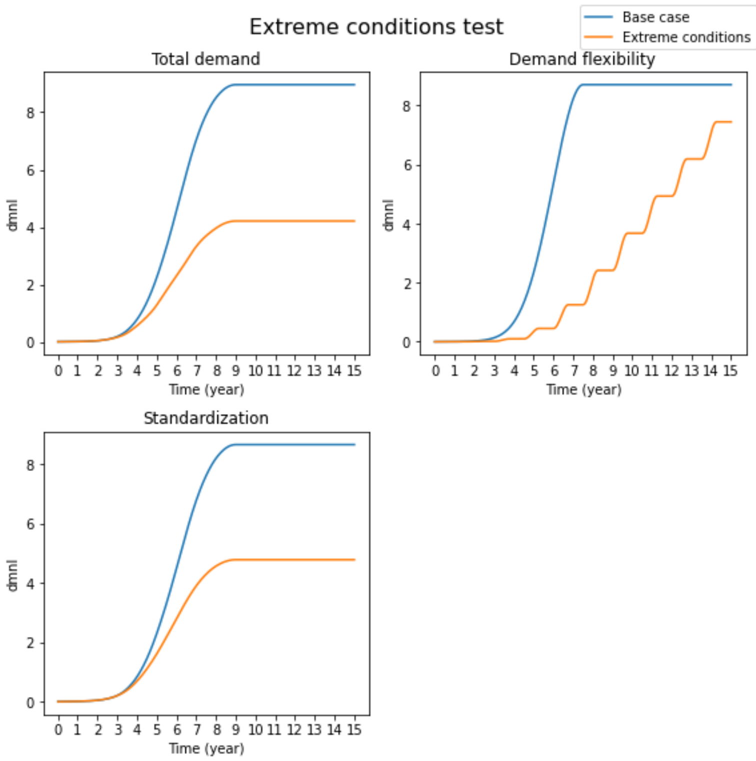

Figure 5.6: Extreme conditions test

In conclusion, we can say that the model is considered valid as it has successfully passed all tests, though with some modifications.

5.4. Experiments

The aim of the experiments is to understand how the *Total demand*, or number of purchases, changes when the system changes. Here, the system can change in four ways; when the *Growth rate standardization* increases or declines, when the market preference shifts, when the importance of *Standardization* relative to *Demand flexibility* changes, leading to an adjustment of *Market preferences*, and when *Market characteristics* is multiplied instead of added in *Change in probability of purchase*. The first three are parameter changes, whilst the last requires a structural change in the model.

5.4.1. Experimental Setup for Parameter Changes

The experimental setup is based upon a change in *Market characteristics*, whereby through the scenarios either *Demand flexibility* or *Standardization* dominates, until they become equal in the fifth scenario. The value for *Market characteristics* in each scenario is combined with a change in *Growth rate standardization* and a shift in the *External landscape*. Table 5.1 shows the different values that these parameters can take in the different scenarios.[8] The growth rate can either be slow (0.5), normal (1), or fast (1.5), and the *External landscape* can begin in a phase where the technology is preferred ($\sin(\omega t)$) or in one where it is not ($\cos(\omega t)$).[9] The combination of these values leads to a total of 23 experiments.[10]

[8]For a comprehensive overview of all experiments, see Appendix C.
[9]In this case $\omega = \frac{2\pi}{T}$, see Equation 5.6.
[10]The value *Market characteristics* is in scenarios 1 and 2 neither 0 nor 1. This is a result of the possible multiplication in *Change in probability of purchase*. If one of the values in this series were zero, the variable would remain at zero and the system would not

Table 5.1: Experimental setup

	Market characteristics	Growth rate standardization	External landscape
Scenario 1	0.01	1	sin(ωt) / cos(ωt)
Scenario 2	0.99	0.5 / 1.0 / 1.5	sin(ωt)
Scenario 3	0.25	0.5 / 1.0 / 1.5	sin(ωt) / cos(ωt)
Scenario 4	0.75	0.5 / 1.0 / 1.5	sin(ωt) / cos(ωt)
Scenario 5	0.5	0.5 / 1.0 / 1.5	sin(ωt) / cos(ωt)

5.4.2. Experimental Setup for Structural Change

The structural change requires a change in Equation 5.7, whereby the rates of *Standardization* and *Demand flexibility* are not added but multiplied. In the results, we will see that this creates a change in the trajectory of the variables, but not in their relative shapes. Therefore, running additional experiments beyond a comparison with the base case was unnecessary.

5.5. Results

The results consist of two parts; results from the experiments with the parameter changes and results from the structural change. In both cases the values for the *Base case* are the same: Market characteristics (MC) = 0.5, Growth rate standardization (GRS) = 1.0, and External landscape (EL) = sin(ωt). It is important to note that no reliable values were used in this model. The only information the model can give is whether certain circumstances lead to a relatively higher or lower level of diffusion. This means the technology is adopted by either more or fewer customers.

5.5.1. Results of Parameter Changes

To begin, we want to understand how changes in *Market Characteristics* impact the diffusion of the innovation. Figure 5.7 shows that markets that are dominated by *Standardization* (MC = 0.99 / MC = 0.75) diffuse at a significantly higher level than markets that are defined by *Demand flexibility* (MC = 0.01 / MC = 0.25). Mathematically, this is the result of the fact that *Standardization* and demand change are both based on the lookup *Dynamic market trajectory* and that they are multiplied in *Changes in probability of purchase*. Thus, the more influential *Standardization* is, the stronger this multiplication effect becomes. This behavior is also in line with §4.3.2 where we hypothesize that the bigger markets in the diffusion phase will be dominated by *Standardization*, whilst the niche markets in the adaptation phase will be characterized by *Demand flexibility*.

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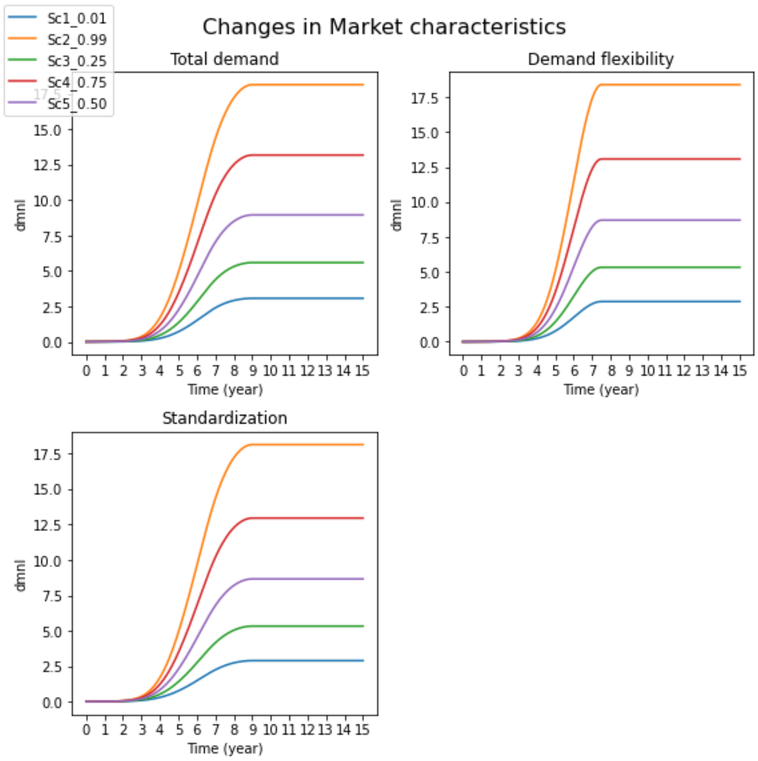


Figure 5.7: Changes in Market characteristics (GRS = 1.0 / EL = sin(ωt))

The strength of the influence of *Standardization* becomes even clearer when we consider the influence of the changes in *Growth rate standardization*. Figure 5.8 demonstrates that the innovation diffuses at a much higher rate when the GRS is 1.5 compared to 0.5.

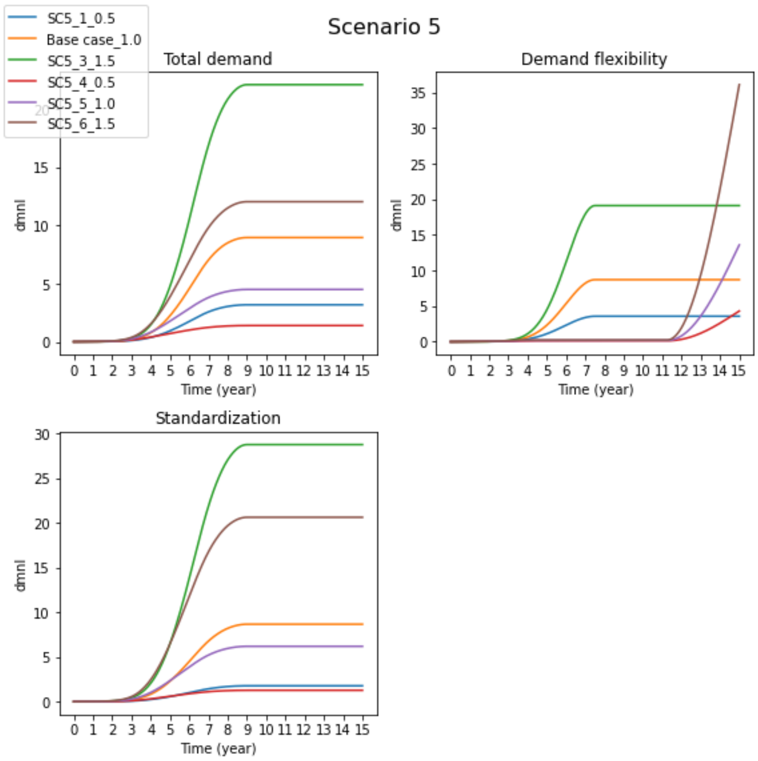


Figure 5.8: Scenario 5 (MC = 0.50)

However, this figure also suggests that a shift in demand preference can significantly impact the diffusion level; it is consistently lower in the scenarios where the preference is negative at the beginning (SC5_4 / SC5_5 / SC5_6). Figure 5.9 illustrates that this is particularly influential in scenarios where the influence of *Demand flexibility* is high.

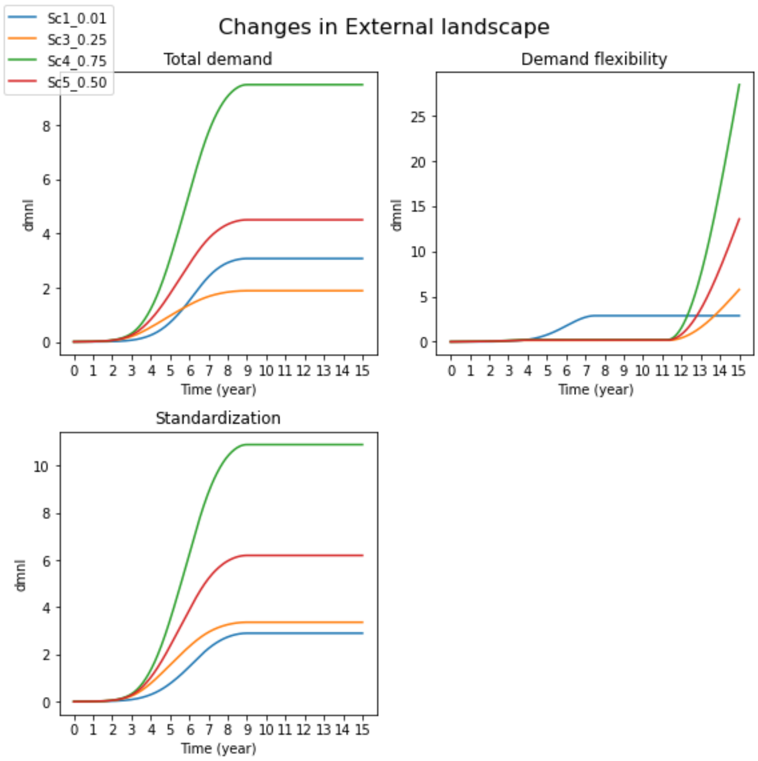


Figure 5.9: Scenario 2 (GRS = 1.0 / EL = cos(ωt))

Figure 5.8 also indicates that, next to a late surge in market preference, a low level of diffusion can result from a low GRS. Figure 5.10 shows the relative influence of these two conditions on all scenarios in which both *Demand flexibility* and *Standardization* play a role. The graphs make it clear that a low GRS consistently leads to a lower level of diffusion. However, in a scenario where the market is mostly determined by *Demand flexibility*, the dislike of the product could lead to an extremely low level of diffusion.

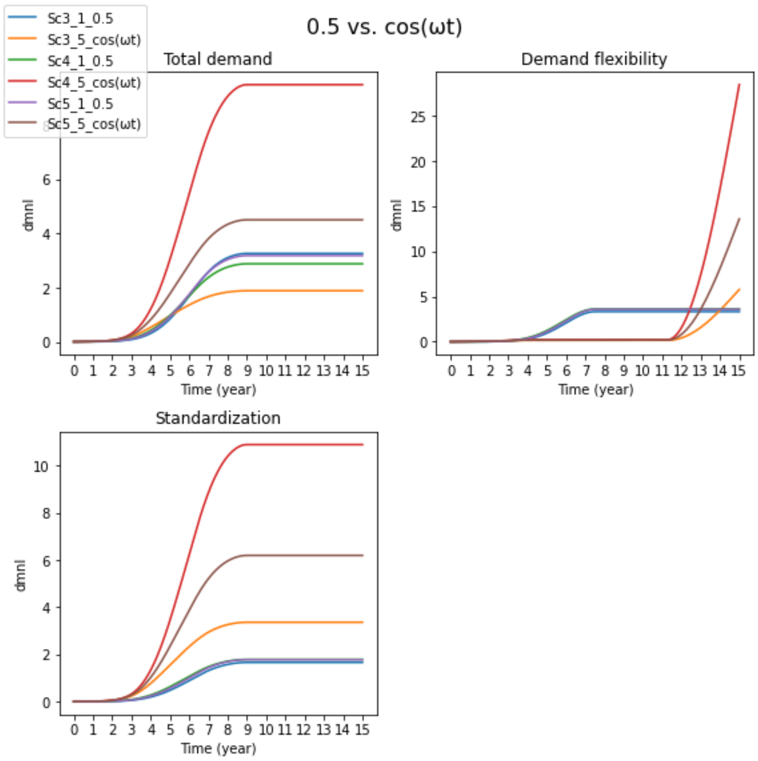
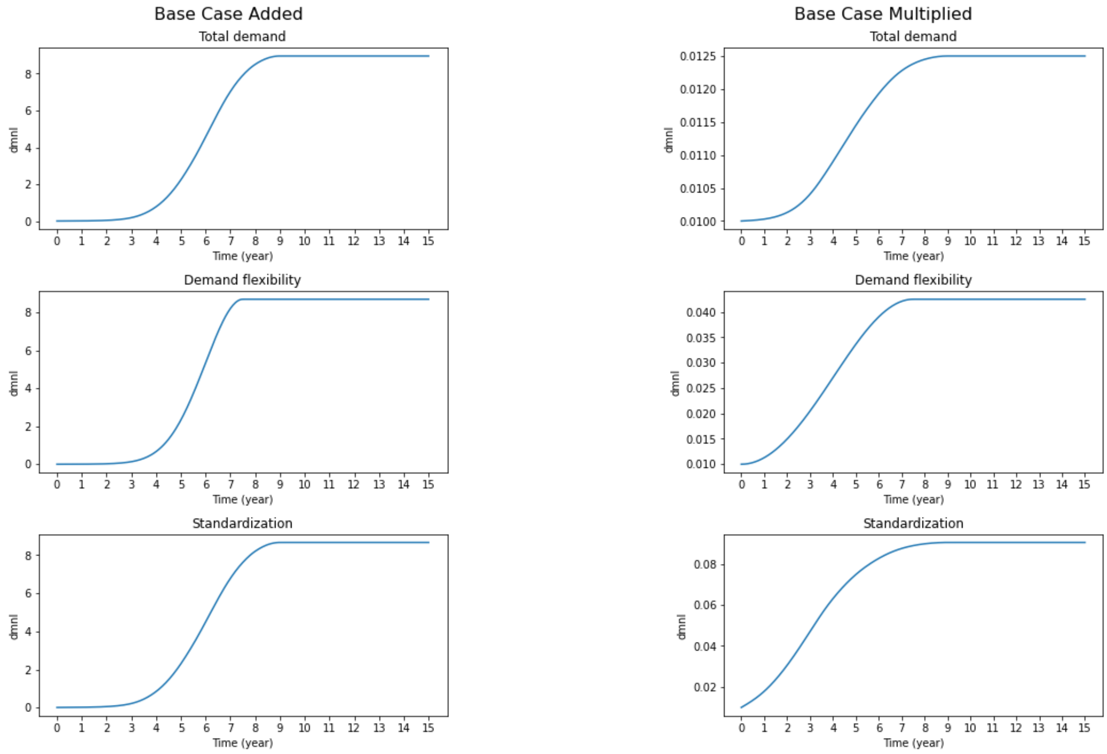


Figure 5.10: 0.5 vs. cos(ωt)

The Figure also shows that it makes no difference whether an innovation with a low GRS enters a market that is dominated by *Demand flexibility* (SC3_1) or a market that is more dependent on *Standardization* (SC4_1).

5.5.2. Results of Structural Change

It is also interesting to know how the behavior of the model changes when the *Standardization* and *Demand flexibility* are multiplied in *Change in probability of purchase* instead of added. Especially, because it invites us to contemplate in which senarios this behavior could be more realistic. We will compare these options only for the base case, as this change does not affect the relative levels of diffusion observed in the parameter changes. Figure 5.11 depicts the change in behavior. A notable difference is that, in the multiplied version, the demand starts diffusing earlier, but it also has a less steep curve. This version would be more realistic than the added version if there is quick adoption by innovative demand of a market that is not swiftly matched by its imitative demand.



(a) Base case added

(b) Base case multiplied

Figure 5.11: Experiment structural uncertainty

5.6. Conclusion

The aim of this chapter was to answer the following sub-question: "How does the number of customers in the TIS change over time?" In order to do so, we made a model that we verified, validated, and experimented with. Since the model only demonstrates the interaction between standardization and demand flexibility, we can draw conclusions about the impact of these factors on the change in purchases. Understanding the impact of the elements on the TIS would require a different model.

The experiments led to the following series of conclusions on the behavior of the system. First, a dominance of standardization leads to a significantly higher level of diffusion compared to demand flexibility. This is in line with our hypothesis in §4.3.2, where we state that larger markets in the diffusion phase are more likely to rely on standardization, whilst niche markets tend to be determined by demand flexibility. Secondly, the best strategy to increase the level of diffusion is by increasing the standardization, especially in markets that are dominated by standardization. However, to avoid a low level of diffusion, it is important to enter the market at a time when the demand prefers the technology, specifically in demand-dominated markets. It is unwise to enter at a time when demand favors another product, as only a very high level of standardization will compensate, and without reaching that level, the opportunity will simply be missed. Thirdly, when the growth rate of standardization is low, the model indicates that the level of diffusion will be low, independent of the dominance of flexibility over standardization. This suggests that it is irrelevant whether an innovation enters a niche market or a main market when standardization is low, which seems to contradict our hypotheses in §4.3.2. This is probably due to the fact that the model does not imply a threshold for standardization in markets dominated by standardization. In reality, these technologies would probably not be adapted by these markets in the first place, which would mean that they are condemned to markets dominated by demand flexibility. In summary, standardization can result in potentially high levels of diffusion, particularly in main markets. However, to avoid low diffusion levels, it's crucial to enter the market when the technology is preferred and simultaneously invest in standardization.

6
Conclusion

Innovation is a risky business, both for the governments aiming to shape their policies around it and the companies who base their existence on it. This is especially true for Radically New Technological Innovations (RNTIs) who are defined by their new functionalities and relatively good price/performance ratios. These technologies tend to fail because, although they are often technologically superior to their competitors, they may not be commercially superior. The aim of this study, in its broadest sense, was to understand why RNTIs are at a disadvantage and how to improve their viability to ensure their success in the market.

To do so, we decided to view the innovation market as a system with two main components: time and elements. In the past, the narrative in Innovation Management was that innovations emerge in *the* market, where they either diffuse and succeed or where they do not diffuse and consequently fail. However, since then, we have discovered that innovations do not simply emerge in their final form on the market, but that they are first developed, after which they are sold in smaller markets in which they get the chance to develop further, and only after they have been successful in these niche markets, they will enter the bigger markets in which they will diffuse. In this perspective of the system the innovation does not simply succeed or fail at a single point in time within one market. Instead, it is given time to develop across multiple markets, where it may fail in some but succeed in others. What is crucial for the viability of most innovations, however, is that it ultimately reaches the large-scale diffusion phase, where the innovation gains enough customers to be viable on an industrial scale. Therefore, in this study, we focus on the transition from the adaptation phase, where innovation exists in niche markets, to the large-scale diffusion phase. To research this transition, we view the innovation not simply as an artifact but as a Technological Innovation System (TIS) that is made up of separate elements that develop individually or through mutual interactions. The cumulative behavior of these elements ultimately determines the behavior of the system as a whole, and therefore also dictates whether the innovation progresses from the adaptation into the diffusion phase. In order to make this transition possible, seven elements all have to be present in the system. These builing blocks of the TIS are as follows: customers, price, performance, production, networks, institutions, and complementary products and services. However, the level at which they are present differs across phases and between technologies. In summary, the system is characterized by its evolution over time. In the long term, it transitions between phases, while in the short term, the interactions between its elements constantly alter its behavior. Therefore, it can rightly be said that the TIS is a dynamic system. Consequently, our aim was to regard it as such in our research. To have a dynamic perspective, we had to introduce a new viewpoint from which to consider the system. We selected System Dynamics Modeling (SDM), because it focuses on representing interactions in systems and its overall development through time, and thus grants us the language to understand TISs in this context.

The great potential and the great challenge of this project lie in first combining Innovation Management and TIS literature and secondly viewing them through the lens of System Dynamics Modeling. On the one hand, it might hold the key to a better understanding of why innovations fail and how to prevent this, but on the other hand, the very key needed to unlock this understanding must first be forged. This first consists of the creation of a perspective on innovation systems in which both their phase transitions and their individual elements can coexist. Secondly, it requires the development of a new language that enables us to describe this system as continuous, despite it being portrayed as discontinuous in the Innovation Management literature. An important component of this new language is making sure that it services the theory and not the System Dynamic Model. A common pitfall is altering the theory to make it fit the model better, rather than designing the model to accurately reflect the theory. On top of that, we also had to make a fourth iteration from an SDM to a simulation model in order to better understand the dynamics in the system. This required a translation from a system dynamics perspective to a mathematical way of thinking.

Having to make these iterations introduced a lot of uncertainty in the study, because we do not yet know what we can pronounce using these new languages that we could not when we viewed the system as discontinuous. As a result, we only have a sense of what can be explored using them, but we lack clarity on the steps to take, whether the question can truly be answered, how long it will take, and what other essential questions might arise along the way. To manage this uncertainty, we posed a number of broadly formulated questions, which were ultimately all at least partly answered. To that end the research has been divided into five sub-questions, see the frame 'Research Questions'. First, we developed a method to translate the Innovation Management and TIS literature to System Dynamics Modeling. Next, we used this method to understand the behavior of the system. To make sure that the model had a clear focus on showing the overall behavior of the system, we used a top-down method. This consisted of first asking for the overall change in the number of customers (sub-question 2). Then we went more into detail and researched the components of the SDM (sub-question 3) and their interactions and collective behavior (sub-question 4). Finally, in sub-question 5, we looked at the dynamics that drive the innovation's progression from the adaptation phase to the diffusion phase. Having explored these questions in the previous chapters, we will now answer them here. These answers will also help address the main research question.

Research Questions

How can we develop a System Dynamics Model (SDM) that accurately portrays the interactions among elements within the Technological Innovation System (TIS), shedding light on the system's behavior across different phases and identifying factors hindering the progression of the adaptation into the diffusion phase?

1. How can the existing information on the TIS be analyzed in such a way that it unveils the dynamic behavior of the system?
2. How does the number of customers in the TIS change over time?
3. How can the elements in the TIS as summarized by Ortt & Kamp (2022) be defined as quantifiable variables?
4. What behavior do the individual elements display, and how does this behavior influence the behavior of the other elements in the TIS?
5. Which elements or interactions between elements within the TIS dictate whether an innovation progresses to the diffusion phase?

6.1. Conclusions on the Research Design

In order to understand the dynamic behavior of the system across all its phases, we needed to develop a method that combines the knowledge from TIS-literature with the analytical research methods used in System Dynamics (SD). Therefore, the following question was asked: "How can the existing information on the TIS be analyzed in such a way that it unveils the dynamic behavior of the system?"

When contemplating this question, we discovered that the main goal of this method would be to translate the information from the literature into an SDM. To make this possible, the method would have to aid us in finding a consistent definition of all elements that could be quantifiable, it would have to help us uncover the relationships between the elements, and it should give us the guidelines to combine all of this information into an SDM. After contemplating several methods, we selected synthesis, because it allows us to combine existing information into new theories on the behavior of the system. Figure 6.1 shows the three steps this method consists of. First, we have to select literature, which mainly consists of case studies and previous SD research into innovation diffusion, that lends itself to modeling. Secondly, we have to combine all this information into a theory on the behavior of the system as a whole. In order to make sure that the model only shows the fundamental behavior, we employed a top-down method. First, we have to look for graphs that show the overall behavior of the system. If we cannot find those, we can look for interactions among elements, and if these cannot be discovered, we can start understanding the system based on its individual elements. Having gathered this information for all elements, we can fuse it to discover interactions between elements, which in turn will show us the overall behavior of the system. However, before we can call this a theory, it needs to be validated. This can be done using expert interviews or by experimenting with a system dynamic simulation model to see whether its behavior is realistic.

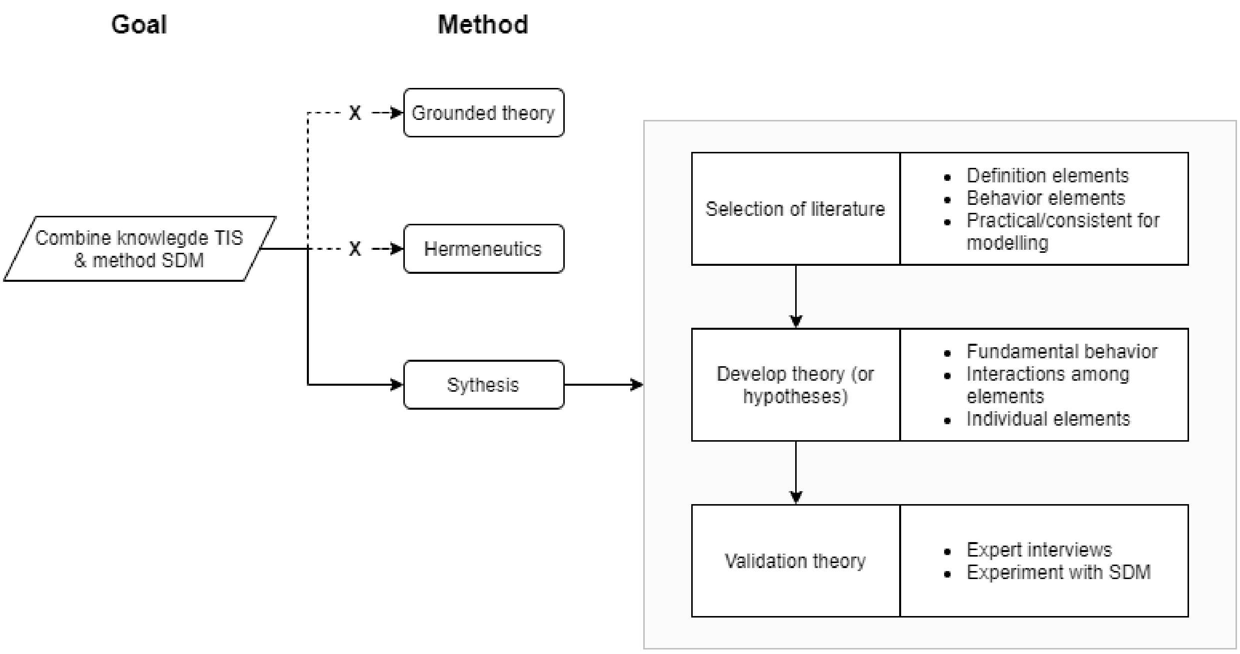


Figure 6.1: Outline method

However, it is important to make two remarks regarding this method. First, that it is based upon one core assumption; that all TISs ultimately exhibit the same fundamental behavior and that it is possible to devise a method to uncover this behavior. Second, that claiming to develop a theory is only accurate if all steps of the method for the full TIS are taken. Since this study has only examined selected elements of the system and has not covered every step, we can only say we have contributed to theory.

6.2. The Design of the System Dynamics Model and Conclusions on the Behavior of Single Markets

In order to better understand the behavior of the TIS we needed to make a model of the system, starting with a Causal Loop Diagram (CLD). The third sub-question forms the basis of this model: "How can the elements in the TIS as summarized by Ortt & Kamp (2022) be defined as quantifiable variables?"

Answering this question might seem like a practical step, just something necessary to build the model. However, defining something as a variable that changes over time and can be assigned a value with a unit can offer a new, broader understanding of the element's content. I therefore invite you to read these definitions and contemplate how it changes your perspective on these elements.[1]

- Customers: The customers are divided within two groups; the innovative customers who buy the product as soon as it enters the market, and imitative customers who only purchase it after others have done so. Their cumulative purchases determine the *Total demand*. For other elements to increase the number of purchases, they must raise the *Probability of purchase*.
- Production: The production element involves two mechanisms: learning-by-doing (LBD) and economies of scale. LBD increases knowledge in the production process, leading to reduced costs over time. As the customer base grows, these costs decrease further, lowering the *Cost per unit*, a process known as economies of scale.
- Performance: The performance is also determined by two mechanisms: LBD and learning-by-searching (LBS). LBD is informed by an increase in production, whilst LBS grows as the investment in R&D-related activities grows.
- Price: The price consists of a *Price per unit*, which is determined by a *Cost per unit*. This cost price is defined by the production and the investment in R&D. Due to a phenomenon known as the pig cycle, the price is oscillatory.
- Networks: In this model, networks are defined as formal organizations whose influence on the system is measured by its collective resources. This network can produce two kinds of knowledge; knowledge it has acquired from the organizations that are part of the network and knowledge that is generated through participation in the network. Next to knowledge, the network also produces influence over other actors through the growth of its power and reputation.
- Institutions: Two concepts play a role in institutions: legitimacy and standardization. An increase in legitimacy signifies a rise in customer trust in the product. This growth is partly emergent but can also be influenced by factors such as increased standardization. When a product initially enters the market, it can take various forms. However, through market mechanisms, industry guidelines, and government regulations, the product eventually becomes standardized into a final form. The concept of standardization automatically introduces its opposite; changes in the product preferences of customers or *Demand flexibility*. This variable displays long term oscillatory behavior.
- Complementary Products and Services: Complementarities are all the products and services that

[1] Table 3.1 also provides definitions for all variables.

serve the core product and thus enhance its *Probability of purchase*. In this model, only non-essential complementarities are represented, as essential complementarities primarily focus on enabling the product to enter the market rather than fostering the overall growth of the TIS.

In order to develop a variable that can used in a mathematical model it has to be assigned a unit. Here, the model is a representation of the system at its most fundamental level, and it is thus not assigned to a real-life case and cannot derive dimensions from real-world scenarios. All variables are therefore dimensionless. In practice, this means that we use rates of change that align with the trajectories we can identify for the variables.

With the elements defined, we had a foundation to identify their variables and understand how they are interconnected. This resulted in Figure 6.2. Based on this figure, we can answer the fourth sub-question: "What behavior do the individual elements display and how does this behavior influence the behavior of the other elements in the TIS?"

> What behavior do the individual elements display and how does this behavior influence the behavior of the other elements in the TIS?

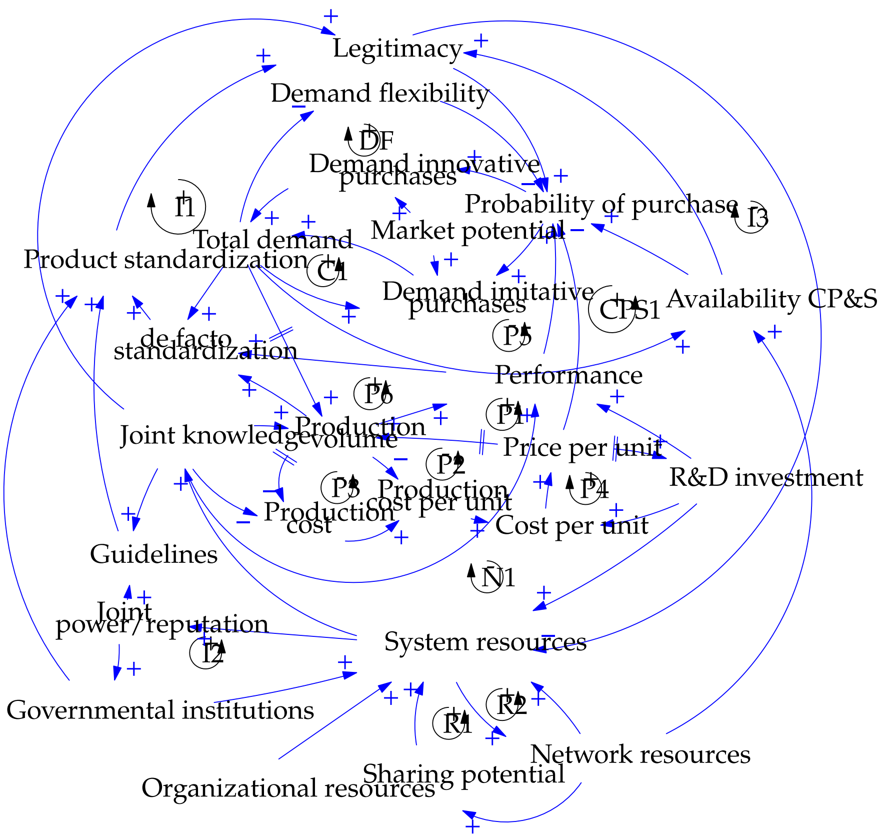


Figure 6.2: Full CLD

It is important to note that this question cannot be answered fully or definitively by this study. Although the CLD in Figure 6.2 provides some insight into the model's behavior, this is restricted to the influence of individual links or short feedback loops. To grasp the complete behavior of the model, it must be simulated. Additionally, since the model is still at the stage of a hypothesis as it has not yet been validated, the following conclusions are valuable but inherently limited.

Starting with the subsystem *Customers* we can conclude that the growth in *Total demand* carries its own tragedy as it is limited by the market potential, which is the potential number of customers for the innovation, and will collapse once this limit has been reached. Even so, *Total demand* has an important role in the system as it drives the growth of many other elements and indirectly also its own growth. Other important drivers in the system are the growth in production, the growth of the network, and the availability of complementarities. Apart from these drivers, we can also discern some influential mechanism in the system. Firstly, the CLD demonstrates that production and price are linked through a feedback loop. Since price is oscillatory, production also exhibits oscillatory behavior. However, whilst price decreases over time, production increases. Secondly, a key factor concerning price is *R&D investment*. A high price results in increased investment which leads to a higher price. Thirdly, *R&D investment* has an ambivalent influence on *Probability of purchase* as it leads to a higher price and a higher performance. The fourth mechanism is the relation between *Legitimacy* and the network. The network is an important driver for legitimacy, but if the legitimacy has reached a certain level, the network will decrease its investment in the product, as it will feel that investment is no longer necessary to keep up sales. This could have big consequences, because it could lead to a disinvestment in the elements 'Production' and 'Performance'. Lastly, a strong collaboration between governments and the network leads to a growth in legitimacy.

6.3. Transitions Between Markets

In the previous paragraph, we described how the elements are interrelated and how these interactions result in certain behavior. This behavior exists within a singular market. However, to move through the adaptation phase and progress into the diffusion phase, the innovation has to transition from one market to another. We therefore need to understand what drives these transitions and how the elements of the TIS influence them. To do so, we will consider the fifth research question.

> Which elements or interactions between elements within the TIS dictate whether an innovation progresses to the diffusion phase?

When we first posed this question, we envisioned that we could experiment with a simulated version of the model presented in Figure 6.2. By adding or omitting links, we would be able to amplify the behavior of the model to make a transition possible. This was a somewhat naive idea. In reality, we needed to develop a new theory on how transitions between diverse markets occur, when they are feasible, and how to integrate these concepts into an SDM. Only then could we determine which elements are crucial in transitions and what conditions lead to a successful transition into the diffusion phase.

As stated earlier, we hypothesize that these transitions occur between heterogeneous markets. This is essential in understanding these transitions, because it means that during the adaptation phase the TIS transitions between various markets with distinct characteristics. To succeed in these markets, it must meet each of their specific demands. This explains why it is hard for RNTIs to enter bigger markets. Whilst niche markets will accept its underdeveloped TIS in exchange for its novel functionalities, the bigger markets that define the diffusion phase will only buy a product with a low price, high performance, and high legitimacy.

However, this does not mean that it is impossible for innovations with an underdeveloped TIS to enter the diffusion phase. There are two routes to accomplish this. The first is self-evident; the TIS can be refined to make it more attractive to bigger markets. In practice, this often means that it must initially enter several niches during the adaptation phase. This allows it the time and resources it needs to develop, after which its TIS is mature enough to align with the demands of the main markets. The second is, when the market lowers its demands to the current level of the TIS. This shift is often the result of large scale events such as demographic changes, natural disasters, or (economic) crises. Geels (2006) calls these shifts 'changes in the external sociotechnical landscape'. In conclusion, in theory there are three ways for an innovation to transition to a new market and ultimately to reach the diffusion phase. First, by developing its TIS. Second, through a shift in demand preference as a result of external landscape changes and third, through a combination of both.

When we view this theory in the context of the CLD, a particular mechanism stands out; the dynamic between standardization and demand flexibility, see Figure 6.3. We concluded earlier that over time the product will standardize. This process results in the lock-in of a technology, meaning that the customers in this market come to prefer this product over all others and are hesitant to change. Thus, the lock-in of one technology also always results in the lock-out of all others. In Figure 6.3, which is a simplification of the CLD, lock-in is a result of a continuous growth in standardization that leads to a high *Probability of purchase*. This probability can be reduced through an increase in the *Demand flexibility*, which is a result of a shift in the *External landscape*. The likelihood of a previously excluded technology entering the market depends on two key factors. First, whether the shift in the landscape positively or negatively impacts the *Probability of purchase*, represented by an oscillating curve. Second, which of the two variables—*Standardization* or *Demand flexibility*—has a greater influence on the *Probability of purchase*. We hypothesize that niche markets will mostly be defined by the demand-side, whilst main markets in the diffusion phase will mostly rely on standardization. As a result, RNTIs are more likely to succeed in niche markets whose preference has shifted towards the product.

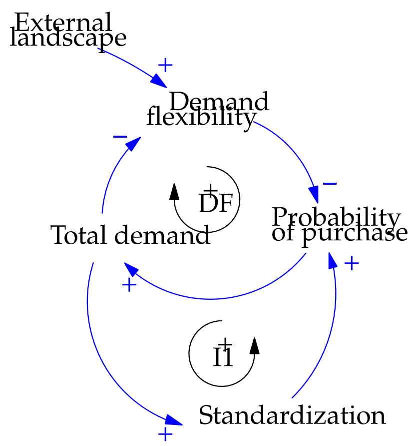


Figure 6.3: CLD including the external landscape

To answer the research question, whether an innovation is able to transition to the diffusion phase is either depended on the level of development of its TIS, the change in demand preferences or a combination of both. As markets in this phase are more likely shaped by a high level of standardization than by flexibility, it's particularly important to focus on increasing standardization. The CLD suggests that, hypothetically, standardization can be most directly strengthened by increasing demand, performance, production, network resources, and institutions.

6.4. The Cumulative Change of Customers

At the start of this research we asked a very ambitious question.

> How does the number of customers in the TIS change over time?

Here, we hesitantly formulate a first answer, using the simulation model we described in Chapter 5. As this model specifically shows the influence of standardization and demand flexibility on the number of purchases and works with trajectories, we can only draw conclusions on how these specific variables change the level of diffusion of the innovation.

First, the model confirms our hypothesis that bigger markets are determined by standardization, while niche markets tend to be more flexible. Second, it shows that achieving a high level of diffusion requires investment in standardization. However, to prevent low diffusion levels, it is crucial to enter the market when the technology is preferred and to avoid low standardization, particularly in markets that may have a threshold for standardization.

6.5. Main Research Question

By addressing the sub-questions, we can now answer the following main research question.

> How can we develop a System Dynamics Model (SDM) that accurately portrays the interactions among elements within the Technological Innovation System (TIS), shedding light on the system's behavior across different phases and identifying factors hindering the progression of the adaptation into the diffusion phase?

To create an SDM that illustrates the interactions between the building blocks, we need to formulate a synthetic theory encompassing all these interactions and validate it. Additionally, to understand phase changes in this context, we must modify the SDM to account for market transitions. Having taken the initial steps in this direction, we recognize that achieving high levels of diffusion—and thereby increasing the likelihood of entering the diffusion phase—requires investment in standardization growth while also avoiding low standardization and markets that do not favor the technology.

7 Discussion

"Reality is the rock against which our various ships always founder, and as such it must be acknowledged and revered, however elusive it may be."
- Graham Harman, Object-Oriented Ontology: A New Theory of Everything

After designing the research, conducting it, and drawing conclusions, the time has come to reflect. While this reflection could focus on the process or the outcomes, given the fundamental nature of this research, I mostly want to use this chapter to reflect on the foundations of the research; its methods and its underlying assumptions. With this in mind, I will break down the discussion into four layers; the methodology, the model design, the research process, and the results.

7.1. Reflections on the Theories and Methods

In this section, I will consider the three pillars of this study; System Dynamic Modeling, Ortt's evolution model, the literature on Technological Innovation Systems (TIS), and the synthesis method that was devised for this study. I will reflect on what insights this research provides about each and explore what could have been done differently.

7.1.1. System Dynamics Modeling

It is unique to the SDM method that it considers the object of its model a system whose behavior is a result of its structure and is characterized by non-linearity Nava Guerrero et al., 2016. For this reason, SDM is ideal for this study, because it allows us to see how the high-level relations between the building blocks lead to the phase changes in the evolution model. However, having a method to make the modeling of these systems possible is not the same as understanding why these systems exist and why they can be represented this way. The method itself is based on practical application, and therefor has not gone beyond stating these paradigms. However, I would argue that to apply these paradigms consistently and accurately, we must first gain a deeper understanding of them.

Appendix D describes the first steps I took on this path. In this essay, drawing on Aristotle, I state that a variable in a feedback loop is not merely a cause that transitions into a consequence; rather, it operates simultaneously as both cause and consequence, with the causes being in effect (*energeia*) in the consequence. I also argue, following Stiegler, that the way the model is designed and presented determines its power over the audience. Both of these insights were instrumental in developing this model. The new understanding of feedback loops was particularly valuable, as I could not assume feedback simply because I observed it in real life. Instead, I had to examine which variables were in effect in a given variable and whether that variable was one of them. Stiegler's retention theory also clarified the importance of clearly articulating my assumptions. In this essay, I explored only two avenues. Other potential avenues include examining the consequences of rationally distancing ourselves from the systems we observe, drawing on Hannah Arendt's theory of the shifting Archimedean point in *The Human Condition*, or analyzing the conceptualization of time in SDMs through Heidegger's interpretation in *Sein und Zeit*. I would be very curious to know how answering these questions might help us employ the method more consistently and accurately.

Another reason why a more philosophical view of SDM might be beneficial is because of the term 'System Dynamic Model'. Or more precisely, because of the lack of specificity in this term. Both the conceptual model in Figure 6.2 and the simulation model in Figure 5.2 are SDMs, though they are designed differently, serve different purposes, and produce different types of results. And that is just for SDMs; the word 'model' has many more meanings.[1] I therefore believe that it would be beneficial to the modeling sector to develop a vocabulary that includes terms to clearly differentiate between all these various models.

In addition to gaining a better understanding of SDM, we also need to consider whether other methods would have been more suitable for the research. As mentioned, SDM was chosen as a method because it can model both the relationships between elements and phase changes. In Chapter 5.1, we also established that it can simulate market heterogeneity and handle multiple markets simultaneously, thereby illustrating how an innovation transgresses through markets over time. However, when we consider other simulation methods, heterogeneity has always been the domain of Agent Based Modelling and in recent years the call to combine simulation methods has grown stronger Nava Guerrero et al., 2016. Therefore, it would be interesting to explore the possibility of combining an SDM of the elements with an Agent-Based Model of heterogeneous markets to see how this integration affects the outcomes of the experiments and our understanding of the system.

7.1.2. Technological Innovation Systems

The challenge in researching TISs is that almost each article defines the TIS differently (e.g. Bergek et al., 2015, Dewald and Truffer, 2011 & Sandén and Hillman, 2011). This is not surprising for a concept that is both new and conceptually complex. These different understandings have been unified in the framework by Ortt & Kamp Ortt and Kamp, 2022, which forms the basis of this study. However, during the course of this study, new challenges with defining the TIS arose that have not been addressed yet. For example, do the customers within the TIS represent the market, or does the TIS exist within a broader market? What can be viewed as the demand or the supply-side? And can a broadly defined innovation, and a TIS be synonyms or are they different? After reviewing the literature, I suspect that all these elements can be unified within the TIS framework. However, the more I pursue this line of thought, the harder it is for me to connect with the concept. I am beginning to wonder if the definition of the TIS has become so broad and abstract that it has lost its connection to reality, and whether it might be more effective to establish a less conceptual, more realistic shared definition.

[1]Some philosophers, such as Descartes and Heidegger, would even say that everything is a model, because its existence depends on our observation.

7.1.3. The Evolution Model

In this section, I want to reflect on two assumptions of the evolution model and how our understanding of them has changed after this research. First, we assume that the system comprises three distinct phases. In the Introduction, Chapter 1, we noted that the number of customers does not drop to zero but instead accumulates over time, and that the behavior of the system varies across these phases. We now understand that the elements comprising the system do not change between the adaptation and diffusion phases; rather, their values shift. In addition, the markets that are prominent in these phases differ in their number of customers and require different levels of standardization for entry. An interesting question that remains is whether the TIS already plays a role in the development phase, or if this phase is only focussed on the development of functionalities.

Second, we only know that an innovation transitions between these phases because it has been observed in a vast number of cases. However, how does an actor know in what phase the innovation is and how to anticipate on phase changes? From this research, we can say that the adaptation phase is characterized by small, flexible markets, whilst the development phase consists of bigger markets that want more standardized products. In general, this should hold true in everyday situations; however, changes in the landscape might shift preferences within markets, leading to sudden transitions between markets and even phases.

7.1.4. The Synthesis Method

Having employed the method designed in Chapter 2, we are now in a position where we can reflect on it. In general, the method was effective because it gave the research direction and did justice to both the Innovation Management and TIS literature and the System Dynamics approach. However, a few points are worth noting. First, the strong emphasis on using the Delft-method to generate a compact model was in hindsight unnecessary. This was due to the limited set of building blocks that helped maintain focus within the model, and the high level of aggregation that made it difficult to find variables at the same level, which automatically kept the model compact. Secondly, there should be more emphasis on incremental design in the method. Once one starts to make the model, one tends to fit the literature to the model, instead of the other way around. To create a representative model, the literature should be revisited at least once to ensure it has been interpreted truthfully. Thirdly, the method focused on identifying graphs that illustrate how a variable's behavior changes over time. Although it was possible to obtain this information for certain variables, such as *Legitimacy*, for most variables the necessary research was lacking.

7.2. The Design of the Models

The advantage of building a fundamental model is that it naturally invites us to ask fundamental questions. Since we created both a conceptual model and a simulation model, we will raise these questions for each.

7.2.1. Reflections on the Conceptual Model

For the conceptual model, I want to reflect on three things; the order of the elements, its general assumptions, and what would change if it was applied to a case study.

To make the Causal Loop Diagram (CLD) in Figure 6.2, I researched the elements in the order displayed in Chapter 3, and added the elements in the same order to the model. I chose this sequence, because I wanted to start with the most basic economic elements: customers, price, performance, and production. Then I added the elements that I saw in the literature; first networks and then institutions, and because I could not find anything about complementary products and services in previously read literature, that was added last. Overall, I think this was a good strategy, as it gave the subsystem *Customers* its driving role in the system. However, the CLD might have been different if *Legitimacy* was added earlier. First, because now *Legitimacy* is not linked to *Price*, *Production*, and *Performance*, even though a connection between e.g., *Performance* and *Legitimacy* seems plausible. Secondly, one could argue that a shift from innovative to imitative demand also indicates a change in *Legitimacy* that is related to the change from explicitly to implicitly granted legitimacy as shown in Figure 3.12. Lastly, in a future version, it may be worth considering the relationship between *Legitimacy* and *Probability of purchase*, as a redefinition might make it possible to merge them into a single variable. Another potential change concerns *R&D investment*. I added this variable before *Joint knowledge*, but if I had researched networks earlier, I likely would have combined these variables, as R&D was later defined as part of *System resources*.

In Chapter 3, I consistently wrote down the assumptions for each of the elements. As an addition it is also interesting to examine the assumptions underlying the full model. I have found three different kinds of assumptions. First, assumptions about the strength of relations. Because the CLD is not simulated, all direct relations are considered equally as strong. Additionally, in the description of the model in Chapter 4, *Demand flexibility* is considered potentially as strong as the rest of the model combined. We also assume that the strength of these relationships does not differ across markets. Secondly, there are assumptions about the dynamics in the system. One is that there is a stark difference between supply and demand in the system; for example, customers are not connected to the networks. A second is that the development of the TIS cannot be abruptly halted, except when the *Market potential* runs out. There's no shock in the system that can drive *Total demand* to zero. Even *Demand flexibility*, with its oscillations, is quite subtle. A third is that there are no links between the *Demand flexibility* and the rest of the CLD, even though one would suppose that the preferences of the actors in the TIS would also influence changes in the external sociotechnical landscape. Lastly, there are some aspects that did not find their way into the model. The most notable is that all other possible elements, particularly Ortt & Kamp's 2022 *influencing conditions* are missing. It is up to a future researcher to determine the placement of these elements in the model. One of these influencing factors is competition. It is indirectly part of the model theory on market transitions, as we assume that markets have certain demands, because there are other products available. However, it is not part of the conceptual model as such. Its absence means that important mechanisms, such as the sailing-ship effect, are not represented in the model. Another key assumption is the context from which this model was developed. All papers used to describe the TIS had a Western origin. Therefore, we make the significant assumption that all innovation systems not only share a similar structure but are also perceived in the same manner Chambers, 2013; de Bont et al., 2019.

The aim of this model was to illustrate the system at its most fundamental and most theoretical level. However, it was also always intended to serve as a foundation for future case studies. At this stage, it is exciting to take a small step into the future and consider how the model might change if applied in that context. The first thing that comes to mind is that links and variables might change. For instance, in the CLD, there is a link between *Governmental institutions* and *System resources* that may not apply to certain TISs. The same holds true for various forms of standardization; it is optional for a network to develop guidelines. The opposite is also possible; a case study might inform the need to add links and variables. For example, currently, the *Cost per unit* is informed solely by production costs, while other expenses could also be relevant. Another option is that, to apply the model to a case study, certain assumptions may need to be adjusted, such as that *Legitimacy* in this model cannot be negative.

7.2.2. Reflections on the Simulation Model

Whilst validating the simulation model in Chapter 5, we realized that the translation from the Causal Loop Diagram to the Stock Flow Diagram required a redefinition of some terms. We also encountered a structural uncertainty that allowed us to see that the same system can be modelled in various different ways. This seems to contradict our most fundamental assumption; that a real universal innovation system exists, which can be represented in a single SDM. This apparent contradiction reminded me of a relatively new philosophical theory called Object-Oriented Ontology (OOO). Graham Harman, its founder, differentiates between a Real Object (RO) and its Sensitive Qualities (SQ). In short, the RO holds the real qualities of an object, whilst the SQ is how the object is perceived by us, the viewers. This means that how an object, in this case a system, shows itself to us, differs from what it really is. And not only do these SQ differ from the RO, they also shift over time; how we perceive an object right now is different from how we perceived it in the past and how we will perceive it in the future. This would have been an easy pill to swallow, had it not been that the theory also claims that it is only these Sensitive Qualities that can be known by us, whilst the Real Object always remains hidden. This means that we only have claims to knowledge and not to truth. It also means that no knowledge can bring us closer to truth, because there is nothing we can do to bridge the gap between the Sensitive and the Real Object. To know an object, it is thus useless to look for a description of the system that is more real than another, because we cannot penetrate the space between the Real and the Sensitive Object. The only question to ask is; which description of its SQ is more useful for this purpose. What is thus problematic in our assumption is not that we assume that a real universal system exists, but that we can describe its singular reality instead of its ever-changing sensitive qualities. The question with regard to our CLD, SFD and simulation model is therefore not which one is more real, because none of them are, but which one is more useful right now Harman, 2017.

7.3. Reflections on the research process

Before diving into the reflection on the results, which largely consists of ideas for future research, I want to take a moment to reflect on the unusual process through which these results were discovered. In theory, the research consisted of three parts; devising a method, executing this method, and obtaining results. In reality, most of our time was spent finding new ways to conceptualize the system, so that results could potentially be achieved later. By the end of the research, we still needed to address our predefined research questions. This left us with many partially answered questions, while also limiting our ability to emphasize the conceptualization process required to reach those answers. This was especially true for sub-question 2, which asks for the change in the number of customers over time. On the one hand, the question provided direction for the research; on the other hand, we might have gained more useful results if we had asked a question more closely aligned with the current state of the research. However, asking this question allows us to reflect on its underlying assumptions. It presumes that all innovations require large markets to survive or succeed. Yet, some companies may prefer to focus on selling a specialized product and not aim to expand into different markets, but rather diffuse within a single one. So, the question could be reframed to focus on the pattern of diffusion or the speed at which it occurs.

In hindsight, a question I would have liked to include is one that delves deeper into the nature of modeling itself. Specifically, what is the purpose of this model? How does representing the real-world system in this limited way actually help us better understand it? In this case, the model was never intended to produce real-world results. Instead, it was designed to offer a dynamic perspective on the system, helping us better grasp the interactions between elements within and across markets. It was built to support the development of a theory on how TISs function. Had we started with this question, we might have had more space to consider not just what the model should include, but how it should be constructed.

7.4. Reflections on Results

With regard to the results, they exist mostly to take the first few steps on the path of this research. There is far more to discover by looking ahead than by reflecting on what has already been done. Here are some suggestions for further research. First, it is crucial that at one point in time Ortt & Kamp's 2022 *Influencing conditions* are added to the model to ensure that it reflects the system as fully as possible. This is especially important in the case of competition. Second, in Chapter 5 we only simulated a small part of the conceptual model. Simulating the full model could provide us with information on how the elements influence each other and how their collective behavior influences the *Total demand*. This would be especially useful for helping us to understand the long-term effects of the extended feedback loops. Third, we also have not developed a computational model capable of displaying multiple markets and the transitions between them. Fourth, it might be interesting to change some assumptions. How would the model change if networks could function as separate entities that might be in conflict with one another? Finally, what characteristics make a market viable and worth investing in for a particular company? When is the customer base large enough, or when are the expectations of the TIS aligned closely enough with its actual functionalities?

In this discussion, we have moved from the very abstract to the very specific. We both wondered whether reality can be known to us, and if the link between *Governmental institutions* and *System resources* exists. This might seem odd, but it is also exemplary for this study, in which we tried to marry a very theoretical idea of Technological Innovation Systems and phase changes with a diverse method to obtain very practical results.

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A

Legend System Dynamic Models

Figure A.1 gives an overview of the shapes used in the System Dynamic Models in Chapters 3 and 5 and their meaning.

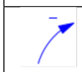
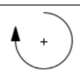
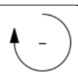
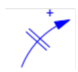
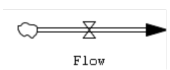
Shape	Meaning
	Positive influence
	Negative influence
	Reinforcing feedback loop
	Balancing feedback loop
	Delay
	Representation of an element
	Stock
	Flow

Table A.1: Legend Causal Loop Diagrams

B

Sensitivity analysis

This appendix is an addition to §5.3 and shows the graphs for the sensitivity analysis. Like the *Total demand* in Figure 5.5, *Standardization* (Figure B.1) and *Demand flexibility* (Figure B.2) are only numerically and not behaviorally sensitive.

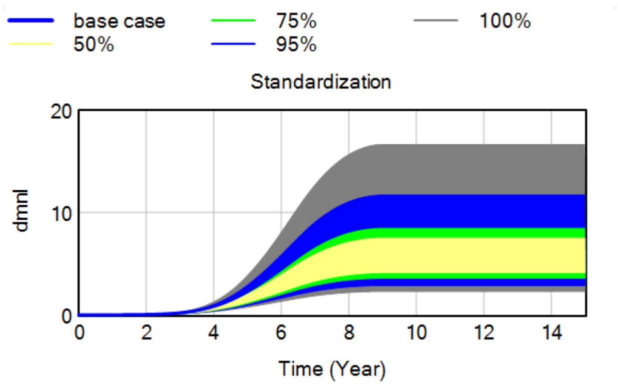


Figure B.1: Sensitivity Standardization

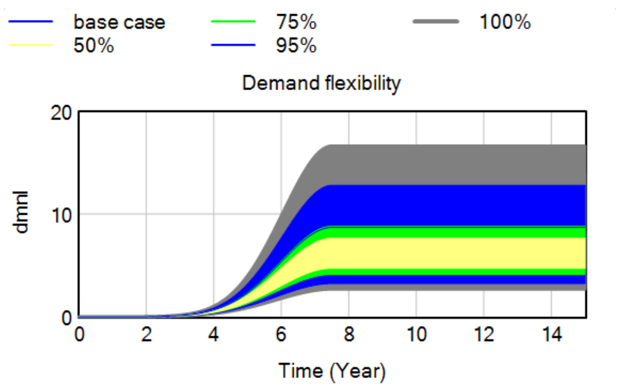


Figure B.2: Sensitivity Demand flexibility

C

Experiments

Table C.1 gives an extensive overview of all the experiments described in §5.4. The column 'Experiment' shows the codes for all the experiments, which is a combination of the scenario, dependent on *Market characteristics*, and the variation within the scenario, determined by *Growth rate standardization* and *External landscape*. Not all variations are included in the experimental setup, as some are not useful. For instance, varying the *Growth rate standardization* in scenario 1 is pointless because in that case, *Standardization* has a negligible impact on the system.

Table C.1: Extensive experimental setup

Experiment	Market characteristics	Growth rate standardization	External landscape
Base case	0.5	1	SIN(ωt)
SC1_1	0.01	1	SIN(ωt)
SC1_2	0.01	1	COS(ωt)
SC2_1	0.99	0.5	SIN(ωt)
SC2_2	0.99	1	SIN(ωt)
SC2_3	0.99	1.5	SIN(ωt)
SC3_1	0.25	0.5	SIN(ωt)
SC3_2	0.25	1	SIN(ωt)
SC3_3	0.25	1.5	SIN(ωt)
SC3_4	0.25	0.5	COS(ωt)
SC3_5	0.25	1	COS(ωt)
SC3_6	0.25	1.5	COS(ωt)
SC4_1	0.75	0.5	SIN(ωt)
SC4_2	0.75	1	SIN(ωt)
SC4_3	0.75	1.5	SIN(ωt)
SC4_4	0.75	0.5	COS(ωt)
SC4_5	0.75	1	COS(ωt)
SC4_6	0.75	1.5	COS(ωt)
SC5_1	0.5	0.5	SIN(ωt)
SC5_2	0.5	1	SIN(ωt)
SC5_3	0.5	1.5	SIN(ωt)
SC5_4	0.5	0.5	COS(ωt)
SC5_5	0.5	1	COS(ωt)
SC5_6	0.5	1.5	COS(ωt)

D

Systeemdynamica: een filosofische verkenning

In 1972 kwam het rapport *The Limits to Growth* uit. Dit rapport confronteerde de wereld met het feit dat haar economische expansiedrift op lange termijn zou leiden tot het ineenstorten van de economie en het milieu. Deze conclusie en de politieke gevolgen ervan zouden op zichzelf al genoeg zijn om het rapport baanbrekend te noemen. Het was echter ook vernieuwend op een heel ander vlak. Het maakte namelijk gebruik van een methode die op dat moment amper een paar decennia bestond: de systeemdynamica (SD) (Meadows et al., 1972).

Om te begrijpen hoe deze methode deze ontdekkingen mogelijk maakte, is het noodzakelijk om haar kort te introduceren. Zoals de naam al zegt, houdt de systeemdynamica zich bezig met systemen. Dit is een vaag begrip dat een brede definitie kent; een systeem is een verzameling variabelen en hun relaties (Backlund, 2000). Er zijn meerdere methodes om systemen te beschrijven, maar de systeemdynamica is uniek vanwege de twee paradigma's waar het op gebaseerd is. Ten eerste stelt deze methode dat het gedrag van een systeem voorkomt uit de structuur van het systeem. Dit betekent bijvoorbeeld dat een recessie verklaard kan worden door de wijze waarop de variabelen in het systeem elkaar beïnvloeden. Ten tweede stelt de systeemdynamica dat veel relaties in een systeem non-lineair van aard zijn. Dit houdt in dat een variabele niet alleen een oorzaak of gevolg kan zijn van een andere variabele, maar ook van zichzelf (Nava Guerrero et al., 2016). Een goed voorbeeld hiervan is het archetype 'Limits to growth' naar het gelijknamige rapport, dat te zien is in figuur D.1. Het model laat zien dat groei, bijvoorbeeld in het gebruik van energiebronnen, zorgt voor meer groei. Deze groei wordt vervolgens beperkt en uiteindelijk gestopt door een *limiting condition*. Figuur D.2 laat dan ook zien dat binnen een *The Limits to Growth*-systeem groei uiteindelijk altijd gevolgd wordt door ineenstorting; dat is de aard van het systeem (Auping et al., 2023, H2.6.2). Binnen de systeemdynamica werkt men onder de assumptie dat ieder systeem gekenmerkt wordt door een combinatie van feedbackloops die over de tijd het gedrag van het systeem versterken, verzwakken of uitbalanceren.

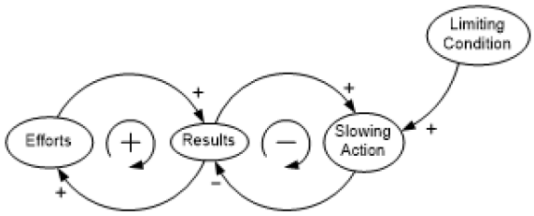


Figure D.1: Model *Limits to Growth* uit Auping *et al.* (2023)

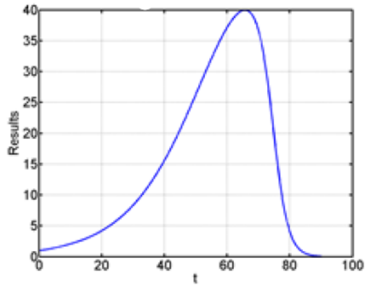


Figure D.2: Gedrag *Limits to Growth* uit Auping *et al.* (2023)

Sinds *The Limits to Growth* is de systeemdynamica steeds invloedrijker geworden. Zij is sindsdien gebruikt om naast economische en ecologische onder andere ook logistieke, politieke en geneeskundige systemen te beschrijven. Deze diversificatie is ook mogelijk door ontwikkelingen in de methode zelf. Door nieuwe, toegankelijkere software is het eenvoudiger geworden om deze systemen te modelleren. Dit succes heeft ervoor gezorgd dat de methode steeds populairder is geworden onder onderzoekers. Dit succes heeft volgens Jay Forrester, de grondlegger van SD, ook een keerzijde. Het heeft ertoe geleid dat sommige mensen de methode gebruiken zonder daadwerkelijk te begrijpen hoe systeemdynamica werkt. Dit is volgens Forrester het gevolg van een gebrekkige opleiding, waarin studenten niet verder komen dan introductiecolleges en zich daarom niet voldoende kunnen bekwamen (Forrester, 2007b). Ik denk echter dat deze crisis niet komt door het slecht uitvoeren van de methode, maar door een gebrek aan onderbouwing ervan. De systeemdynamica is ontwikkeld in de praktijk, aan de hand van casussen. Haar paradigma's zijn dus in de basis niet meer dan de gemene delers in deze casussen. Wij weten niet waarom ze geldig zijn; wij weten alleen dat dit blijkbaar zo is. Ik denk dat het essentieel is om deze vraag wel te stellen, omdat het antwoord erop ons misschien kan helpen bij het beter toepassen van de methode.

Het is echter niet mogelijk om in één essay een volledige filosofische basis te formuleren voor een methode die dusdanig complex is. Daarom zal ik mij beperken tot het beantwoorden van twee vragen. Ten eerste probeer ik de aard van een systeem te begrijpen door te onderzoeken wat een feedbackloop is. Ten tweede vraag ik mij af hoe een SD-model met ons bewustzijn interacteert. De eerste vraag zal ik beantwoorden aan de hand van de filosofie van Aristoteles en bij de tweede vraag zal ik te rade gaan bij Bernard Stiegler.

D.1. Feedbackloops in het licht van Aristoteles' vier oorzaken

Wanneer wij ons afvragen wat een feedbackloop is, stellen wij onszelf eigenlijk de vraag hoe wederzijdse causaliteit werkt. Wij willen weten hoe twee variabelen ten opzichte van elkaar zowel oorzaak als gevolg kunnen zijn. Want als ze zowel oorzaak als gevolg kunnen zijn, wat is dan het onderscheid tussen deze twee begrippen?

Om deze vraag te beantwoorden, kunnen wij te rade gaan bij de vader van de oorzakenleer: Aristoteles. Hij stelt dat alles wat bestaat, en dit moet in de breedste zin van het woord genomen worden, vier oorzaken kent. Ten eerste bestaat het uit een materiaal, de *causa materialis*. Ten tweede heeft het een vorm, de *causa formalis*. Ten derde kent het een doel, het bestaat omwille van iets, de *causa finalis*. Ten slotte wordt het bewerkstelligd, de *causa efficiens* (Heidegger, 1954, p. 9-13). Een goede manier om de vier-oorzakenleer te begrijpen is door het toe te passen op het huis. De *causa materialis* van het huis zijn de stenen en het hout. Zijn vorm is vaak een kubus met een puntdak. Zijn doel is het bieden van onderdak; het zijn van een woonplaats. Zijn *causa efficiens* is de timmerman, die het hout en de stenen verwerkt tot een woning.

Het interessante van de vier-oorzakenleer is dat het ons op een nieuwe manier leert kijken naar de relatie tussen oorzaak en gevolg. Dit wordt bijvoorbeeld duidelijk in de definitie die Aristoteles gebruikt van het woord *doel*. Het Griekse woord voor doel, *telos*, duidt niet, zoals in de moderne taal, op een eindpunt. Het duidt niet op het moment dat het huis af is. In plaats daarvan wordt het doel bereikt zolang het gevolg zijn wezensbepaling, of eenvoudig gezegd; zijn functie, vervult. Het huis bestaat bijvoorbeeld, zodat het bewoont kan worden. Zolang het huis dus bewoond wordt, vervult het zijn wezensbepaling. De *telos* van het bouwen van het huis is dus ook niet het voltooien van het gebouw, maar het bewonen ervan. Kortom, in de filosofie van Aristoteles is het doel geen eindpunt, maar het in werking zijn van de wezensbepaling van het gevolg. Het doel, evenals de andere oorzaken, verdwijnt dus ook niet wanneer het gevolg ontstaan is. In plaats daarvan blijven zij aanwezig in het gevolg. Zij blijven bestaan in het stenen, kubusvormige, robuust gebouwde, bewoonde huis.

Wat vertelt deze definitie van het doel ons over het onderscheid tussen oorzaak en gevolg? Het laat ons zien dat de oorzaak niet gescheiden kan worden van het gevolg, nadat dit gevolg is ontstaan. In plaats daarvan blijft de oorzaak voortdurend werkzaam in het gevolg. Dit leert ons iets fundamenteels over de aard van de feedbackloop. Zoals eerder gezegd, zijn de variabelen in een feedbackloop ten opzichte van elkaar zowel oorzaak als gevolg. Dit is moeilijk te begrijpen wanneer wij oorzaak en gevolg als opeenvolgende stappen in een reeks beschouwen. Aristoteles toont ons echter dat een gevolg geen eindpunt is, maar een verzameling van oorzaken die constant in werking zijn om het gevolg te construeren. De oorzaak bestaat dus niet *voor* het gevolg, maar *in* het gevolg. Wanneer wij een feedbackloop willen begrijpen, volstaat het dus ook niet om onze aandacht slechts te richten op specifiek gedrag dat het op een zeker moment in het systeem veroorzaakt heeft. Dan zouden wij namelijk de neiging krijgen om te gaan analyseren hoe de oorzaken, de variabelen, zo op elkaar afgestemd waren dat dit gedrag op dit moment heeft kunnen ontstaan. Dan scheiden wij de oorzaken van het gevolg. In plaats daarvan moeten wij kijken hoe de oorzaken over de tijd dat de feedbackloop bestaat continu van invloed zijn op diens gedrag. Wij moeten de feedbackloop niet zien als een aaneenschakeling van oorzaak en gevolg, maar als een continuüm dat blijvend *in werking* is.

Wij weten nu dat een feedbackloop *is*, wanneer het *in werking* is. Daarmee is onze vraag beantwoord. De vier-oorzakenleer roept echter nog twee andere interessante vragen op. Namelijk, wat is het doel, de *causa finalis*, van een feedbackloop en hoe kan hij tot stand gebracht worden (*causa efficiens*)? Zoals gezegd is bij Aristoteles het doel het in werking zijn van de wezensbepaling, maar wat is de wezensbepaling van zoiets abstracts als een feedbackloop? Om het wat minder abstract te maken kunnen wij kijken naar de technische definitie van een feedbackloop. Technisch gezien is een feedbackloop een systeem van variabelen die zodanig met elkaar verbonden zijn dat ze een cyclus vormen. Dit betekent dat elke variabele in het systeem uiteindelijk zichzelf beïnvloedt (Auping et al., 2023). Deze systemen kennen vaak een hiërarchie. In kleine systemen wordt de hiërarchie bepaald aan de hand van de invloed van individuele variabelen. Echter, in grotere systemen doen de variabelen er eigenlijk al niet meer toe en houden wij ons bezig met het rangschikken van feedbackloops binnen feedbackloops. En feedbackloop kan dus ook gedefinieerd worden als een systeem dat gestructureerd is volgens een hiërarchie. Deze definitie biedt ons een nieuwe ingang in het werk van Aristoteles. Hij beschrijft in de *Politica* namelijk ook uitgebreid systemen die gekenmerkt worden door een hiërarchie. Hij gebruikt daar alleen niet het woord 'systeem' voor, maar huishouden, gemeenschap of *polis*. In zijn werk analyseert hij deze samenlevingsverbanden en beschrijft hij hun samenstelling, wat hun wezensbepaling is en hoe hiernaar gehandeld moet worden. Een huishouden bestaat volgens hem bijvoorbeeld uit vier componenten; een man, een vrouw, kinderen en slaven. Allen hebben een eigen taak, die overeenkomt met waar zij toe in staat zijn. Het is bijvoorbeeld de taak van de slaaf om te dienen en van de man om te leiden. Tussen deze vier onderdelen bestaat drie soorten relaties; die tussen meester en slaaf, man en vrouw en vader en kind. Deze relaties bestaan, omdat de taken van verschillende leden elkaar aanvullen. Er is bijvoorbeeld een wederzijdse afhankelijkheid tussen meester en slaaf. De slaaf is volgens Aristoteles niet in staat zichzelf te leiden en kijkt daarvoor naar de meester. Tegelijkertijd heeft de meester de slaaf nodig om in zijn dagelijkse behoeften te voorzien. Wanneer alle leden hun taak uitvoeren, wordt het doel van het huishouden bereikt: het voorzien in de dagelijkse behoeften van zijn leden. Dit principe geldt ook voor de andere gemeenschapsvormen die Aristoteles beschrijft. Ze worden allemaal gekenmerkt door een vaste groep leden, elk met een eigen taak en plaats binnen de hiërarchie. Als ieder lid zijn taak uitvoert, wordt het doel van de gemeenschap bereikt (Aristoteles, 2011, p. D1).

Wanneer wij de gemeenschappen van Aristoteles beschouwen als een systeem van variabelen en de relaties daartussen, dan valt het op hoe zeer deze gemeenschappen gericht zijn op harmonie. Het doel van het huishouden is misschien het voorzien in de behoeften van haar leden, maar het doel van het huishouden *qua* systeem is het verzamelen van alle onderdelen en het in balans houden ervan. Alle leden moeten immers aanwezig zijn en hun taak uitvoeren om te zorgen dat het huishouden functioneert. Hetzelfde zien wij bij systemen die wij met behulp van feedbackloops beschrijven. Op lange termijn bereikt een dergelijk systeem ofwel een equilibrium, of het sterft uit. De enige manier voor het systeem om te overleven is door te zorgen dat zij bestaat uit alle essentiële onderdelen en dat de relaties tussen deze onderdelen zo functioneren dat het systeem in balans blijft. Ieder systeem, iedere feedbackloop, heeft dus als taak om zijn variabelen en subsystemen te ordenen en in balans te houden. Dat is dan ook zijn *telos*; het harmoniëren.

Dat brengt ons bij de *causa efficiens*, want wie of wat is het die deze harmonie bewerkstelligt? Dat is een brede vraag die neigt naar het metafysische, want wat maakt systemen? Een schepper? Een oerknal? Het is daarom zaak om deze vraag te specificeren door hem toe te passen op systemen die vaak beschreven worden in systeem dynamisch onderzoek. Dit zijn altijd systemen die wij als mens in ieder geval deels kunnen beïnvloeden. Bijvoorbeeld doen door een variabele aan te passen of een relatie toe te voegen. Wij kunnen dus tot op zekere hoogte een systeem bewerkstelligen. Dat betekent dat wijzelf de *causa efficiens* zijn. Wij zijn echter niet de *causa efficiens* van een doel; een gevolg dat wij tot stand brengen en vervolgens achter ons laten. Wij zijn de *causa efficiens* van een *telos*. En die *telos* is het continu in balans houden van het systeem. Dit betekent dat ons werk nooit af is. Wanneer wij een interventie in een systeem beginnen om het in balans te brengen, moeten wij die interventies blijven uitvoeren om het systeem in balans te houden. Dit is in contrast met de methodologie van de systeemdynamica. In de systeemdynamica zijn wij altijd op zoek naar de *magic fix*. Wij denken dat er een manier is om het systeem zo af te stellen dat het in balans blijft. Aristoteles leert ons echter dat het tegenovergestelde waar is. Een systeem maak je niet, die onderhoud je.

In de afgelopen paragrafen hebben wij aan de hand van de vier-oorzakenleer vele aspecten van feedbackloops verkent. Wij hebben ons afgevraagd wat een feedbackloop is, welk doel het dient en door wie het wordt bewerkstelligd. Dit leidt ons tot een drietal conclusies. Allereerst is een feedbackloop een verzameling van oorzaken die constant het gedrag van een systeem construeren. Ten tweede is het doel van een feedbackloop om te harmoniëren. Als laatste wordt deze harmonie bewerkstelligt door de mens die steeds opnieuw de interventies in het systeem pleegt.

D.2. Retentie en bewustzijn: de invloed van systeemdynamica op het denken

Een ander aspect van systeemdynamica waar ik aandacht aan wil besteden is de wijze waarop het interacteert met ons bewustzijn. Een goed SD-model toont hoe het gedrag van een heel systeem zich in de loop van de tijd ontwikkelt. Dit geeft opdrachtgevers een vollediger inzicht in hun eigen systemen. Hierdoor komen zij vaak tot de ontdekking dat hun oorspronkelijke mentale model van het systeem niet overeenkomt met de werkelijkheid (Auping et al., 2023).

Jay Forrester vertelt in een artikel over één van zijn eerste ervaringen met een dergelijke verandering in denken. Hij deelt een anekdote die plaatsvindt kort nadat hij in 1969 een van de eerste belangrijke SD-studies heeft afgerond. In deze studie vraagt hij zich af hoe steden economisch gezien het best ingericht kunnen worden en, zoals vaak het geval is bij SD, trekt hij een verrassende conclusie. Hij concludeert dat goedkope huisvesting armoede veroorzaakt, want, zo laat zijn model zien, de economie van een gebied is vaak niet groot genoeg is om in het levensonderhoud van een groeiende groep inwoners te kunnen voorzien. Wanneer hij zijn bevindingen deelt met beleidsmakers stuit hij op veel weerstand. Ze staan namelijk haaks op hun beleid dat juist gericht is op de bouw van goedkope woningen in Amerikaanse binnensteden. Zo is het ook het geval bij een vertegenwoordiger van de New Yorkse wijk Harlem. De eerste keren dat Forrester hem spreekt stelt hij zich uitermate kritisch op en wil hij de conclusies niet accepteren. Na een tijdje raakt hij echter steeds meer geïnteresseerd en begint hij de methode beter te begrijpen. Uiteindelijk concludeert hij dat Forrester wel degelijk gelijk heeft. Of, zoals Forrester het zelf beschrijft (Forrester, 2007a, p. 350):

> He had all the proof right there in his briefcase. He simply had not realized what his knowledge meant until it was all put together in a new way.

De man uit Harlem leerde dus op een andere manier naar dezelfde informatie te kijken. Kortom, het SD-model leert hem op een andere manier naar de werkelijkheid kijken.

Deze anekdote roept bij mij de vraag op hoe het mogelijk is dat een SD-model iemands kijk op een systeem volledig kan veranderen. In essentie is dit een vraag naar hoe de mens beïnvloed wordt door externe informatie. Een antwoord op deze vraag is te vinden in de retentietheorieën van Edmund Husserl en Bernard Stiegler.

In zijn boek *Zur Phänomenologie des inneren Zeitbewusstseins* betoogt Husserl dat onze waarneming nauw verbonden is met onze herinnering. Hij stelt dat wanneer wij iets voor de eerste keer zien, wij het nog niet in de context van het geheel kunnen plaatsen. Wanneer wij bijvoorbeeld een gedicht lezen, begrijpen wij een strofe alleen in relatie tot de voorgaande strofes, maar nog niet als onderdeel van het gedicht als geheel. Dit noemt Husserl primaire retentie. Nadat wij het hele gedicht hebben gelezen, kunnen wij erop terugkijken en ons misschien de cadans of de emoties die het opriep herinneren. Dit is de secundaire retentie, waarin onze verbeelding een rol gaat spelen (Stiegler, 2014).

Deze secundaire retentie is ook zichtbaar bij de man uit Harlem. Hij heeft ooit de cijfers in zijn aktetas gelezen, maar nu herinnert hij zich alleen nog de conclusie die hij daaruit trok. Het interessante voor ons is echter dat vervolgens, tijdens de presentatie van Forrester, het SD-model ervoor zorgt dat hij zich die cijfers opnieuw herinnert en zijn eerdere conclusie loslaat.

Deze omslag kan verklaard worden aan de hand van een proces dat Stiegler, in navolging van Husserl, tertiaire retentie noemt. Tertiaire retentie is de identieke herhaling van hetzelfde object. In het geval van het gedicht is dit niet mogelijk wanneer je het zelf leest, omdat elke lezing zich in een nieuwe context bevindt, die ontstaat door jouw eigen veranderende perspectief en omgeving. Het is echter ook mogelijk om een opname van een gedicht terug te luisteren. Volgens Stiegler wordt jouw herinnering dan steeds op dezelfde manier gevormd. Dit heeft gevolgen voor jouw rol in het herinneringsproces. In plaats van dat jij het gedicht steeds opnieuw interpreteert binnen jouw veranderende context, wordt jouw bewustzijn steeds opnieuw geplaatst in de onveranderlijke context van het audiobestand. Hierdoor voeg jij niets meer toe aan het gedicht, maar besta jij alleen nog als ontvanger (Stiegler, 2014).

Dit is de ervaring waar Forrester op lijkt te intenderen. Hij suggereert dat wanneer je zijn model ziet en begrijpt, je niet meer om zijn conclusie heen kunt; je zult het één-op-één overnemen. In de lezing van Forrester is het SD-model dus een tertiaire retentie. Het is een object dat jouw herinnering overneemt.

Volgens Stiegler is dit gevaarlijk, omdat het leidt tot het verlies van individualiteit; jouw verbeelding wordt aan de kant gezet. Het is echter niet alleen een gevaarlijke conclusie, maar ook één die niet geheel lijkt te kloppen. De anekdote vertelt ons namelijk dat de cijfers over Harlem nog geen onderdeel waren van Forrester's analyse. De vertegenwoordiger verbindt ze zelf aan het model. Hij plaatst het model dus binnen zijn eigen context en trekt vervolgens de conclusie dat Forrester ook voor zijn gebied gelijk heeft. Tegelijk kunnen wij ons ook voorstellen dat deze toepassing overgeslagen wordt. Het gebeurt immers vaak genoeg dat beleidsmakers de adviezen van modelleurs integraal overnemen. Neem bijvoorbeeld de coronacrisis. Een SD-model kan dus zowel een secundaire als een tertiaire retentie veroorzaken. Hoe is dit mogelijk?

Het antwoord op deze vraag ligt niet zozeer in de werking van het model als wel in de werking van ons bewustzijn. Volgens Stiegler bestaat ons bewustzijn uit twee delen; een deel dat zich spiegelt aan zijn omgeving en een deel dat die ervaringen overneemt en zich eigen maakt. Een voorbeeld hiervan is de menselijke neiging om anderen te citeren. Het citaat zelf is dan onorigineel, maar de keuze van het moment of de intonatie bij het uitspreken zijn afhankelijk van het individu. Stiegler vat deze theorie als volgt pakkend samen (Stiegler, 2014, p. 28):

> 'Consciousness' is never constituted purely, simply and originally, in itself: it is always both a little bit monkey and a little bit parrot. It always inherits what it is not - this is its 'facticity'. And it has 'to be' this inheritance.

Hoe *is* de mens dan in deze erfenis? Volgens Stiegler heeft de mens de unieke gave om zijn herinneringen te binden in materiële objecten, zoals monumenten, boeken of liederen. Hij noemt hierbij de stad

Parijs in het bijzonder, omdat het volgens hem een geleefde ruimte is. Het *bestaat* bijna uit materiële herinneringen die ons allen uitnodigen te reageren. Wanneer wij door het *Musee D'Orsay* of over de *Place des Vosges* lopen vervult dit het deel van ons bewustzijn dat erop gericht is om ervaringen over te nemen. Wij verwerken dit vervolgens door middel van retenties. Dit is een proces dat hij epifilogenese noemt (Stiegler, 2014).

Een SD-model is ook een materieel object dat beleidsmakers kan aanzetten tot verschillende vormen van retentie. De eerste keer dat het model wordt getoond, veroorzaakt het altijd een primaire retentie. Of het vervolgens leidt tot secundaire of tertiaire retentie hangt af van de mate waarin beleidsmakers het model en de achterliggende methode begrijpen.

Als beleidsmakers ervan uitgaan dat de conclusie die getrokken wordt met behulp van het model in alle gevallen even geldig is, zoals Forrester lijkt te suggereren, dan is er sprake van tertiaire retentie. De beleidsmaker visualiseert het systeem dan steeds op de manier waarop de modelleur het weergegeven heeft, zonder dat hij de ruimte heeft om daar zelf iets aan toe te voegen.

Het model kan ook gezien worden als een beperkte representatie van het systeem, die bedoeld is om beleidsmakers te helpen hun systemen op een andere manier te begrijpen. Dit leidt tot secundaire retentie, zoals ervaren door de man uit Harlem. Hij richt zich eerst op het begrijpen van het model en de methode. Zo kan hij beide voldoende eigen maken om ze toe te passen binnen zijn eigen buurt en zijn eigen conclusies te trekken. Op deze manier geeft hij ruimte aan beide aspecten van het bewustzijn: hij gebruikt het model van Forrester als referentiepunt, maar behoudt tegelijkertijd zijn individualiteit.

Een SD-model kan dus op twee manieren interacteren met ons bewustzijn. Het kan onze eerdere denkwijzen overnemen of het kan als inspiratie dienen voor een eigen toepassing van de nieuwe kennis. De realisatie dat deze twee paden mogelijk zijn, stelt ons als ontwerpers van het model voor een belangrijk vraagstuk. Willen wij dat beleidsmakers het model zien als de enige ware representatie van het systeem, zodat zij onze bevindingen overnemen? Of willen wij dat zij het model begrijpen, zodat ze het kunnen toepassen op hun eigen situatie en context-specifieke conclusies kunnen trekken? Met andere woorden, willen wij dat het model uitnodigt tot tertiaire retentie of tot secundaire retentie? En als wij eenmaal een keuze hebben gemaakt, hoe kunnen wij het model dan zodanig ontwerpen en presenteren dat het de gewenste vorm van retentie bevordert?

D.3. Conclusie

In dit essay heb ik een eerste filosofische verkenning gedaan van de grondslagen van systeemdynamica. Hierbij ben ik begonnen met het beter begrijpen van de feedbackloop, die in SD de basis van het systeem vormt. Aan de hand van Aristoteles' vier-oorzakenleer heb ik geconcludeerd dat er in een feedbackloop geen sprake is van oorzaken en gevolgen die lineair op elkaar volgen. In plaats daarvan zijn de oorzaken blijvend in werking om de feedbackloop te constitueren. Daarnaast heb ik, geïnspireerd door de *Politica*, vastgesteld dat het doel van een feedbackloop is om te harmoniseren en dat het de taak van de mens is om deze harmonie blijvend te bewerkstelligen.

Vervolgens heb ik onderzocht hoe SD ons denken beïnvloedt door een interactie tussen Jay Forrester en een beleidsmaker te analyseren met behulp van Stiegler's retentietheorie. Hieruit bleek dat een SD-model zowel een secundaire als een tertiaire retentie kan oproepen, afhankelijk van hoe het model gepresenteerd wordt door de modelleur en begrepen wordt door de beleidsmaker.

Deze analyse had als doel de systeem dynamische methode beter te begrijpen om zo inzicht te krijgen in hoe zij zorgvuldiger toegepast kan worden. Wij kunnen nu concluderen dat systeemdynamica een kwestie van lange adem is. Immers, als je eenmaal in een systeem ingrijpt, moet je dit blijven doen. Daarnaast weten wij nu dat er aandacht nodig is voor de rol van communicatie binnen de methode, aangezien de manier waarop de modelleur haar model interpreteert en presenteert bepalend kan zijn voor hoe beleidsmakers naar hun eigen systemen kijken. Dit zijn slechts antwoorden op een aantal eerste vragen. Er blijven genoeg vragen onbeantwoord, zoals 'Heeft ieder systeem een universeel geldende grond?', 'Wat is de grens van een systeem?' en 'Wat is het doel van het uitvoeren van experimenten?'. Het is mijn hoop dat dit essay heeft aangetoond dat het stellen van deze vragen essentieel is voor het waarborgen van de kwaliteit van de systeemdynamica.