Demand Endogenization of Intermediate Products in Supply Chains through a System-Dynamics-based Modularization Concept

by

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Abstract

A huge variety of System Dynamics models have been developed to endogenize short-term demand variations in supply chains. The Beer Game, used as a standard System Dynamics introduction in management courses, is co-responsible for having made these models wide-spread and of high-quality. Surprisingly, models that deal with long-term demand development aren't seen that often. Even in the Special Issue on Supply Chain Management (SCM) in the System Dynamics Review 2004, the editorially responsible team of authors summarizes that this issue plagues firms in innovation driven industries and is often ignored in conventional SCM research. In this paper a suggestion of a long-term demand endogenizing framework is provided, helping to close this gap in recent research. The framework is designed to deal with the diffusion processes of innovative intermediate products. Although most product transactions are intermediate product transactions, many diffusion models are apparently designed to deal with the diffusion processes of end products and not with intermediates as evidenced by the structural causality of these models. With this focus on intermediate products also new ground is claimed. Additionally, generic reusable models and guidelines how to apply the concept to a case under study, makes the aim of the paper, helping to optimize production capacity and inventory planning, practically implementable.

Key Words: Demand endogenization, Bass Diffusion Model, Supply Chain Model, Market Saturation

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1. Introduction and Research Context

Supply chain management (SCM) has a long tradition in the System Dynamics community. More than half a century ago, Jay Wright Forrester published the book Industrial Dynamics which was a major milestone in the System Dynamics literature. Moreover, with Forrester's work the foundation of the SCM field began (Akkermans & Dellaert, 2005). The main issues of Industrial Dynamics in regard to SCM includes demand amplification, swings of inventories, advertising policies, effects of (new) information technologies and decentralized control (Forrester, 1961).

1.1 Research Objective

Bhatti, Kumar, and Kumar (2012) point out recent trends in SCM research. Besides the core issues mentioned above, they name inventory management, time compression in planning, design and integration of supply chains and a new global perspective in supply chain planning and deployment as recent general tendencies covered in the relevant literature. Not incorporating demand endogenously, especially for innovative products in supply chain management, is looked upon as a gap in recent research. The endogenous demand issue "plagues so many firms in innovation-driven industries and is typically ignored in conventional SCM research" as stated by Akkermans and Dellaert (2005, p. 182). The research objective of this paper is to tackle this research gap.

For this purpose a model-based extension for a standard SCM will be developed to incorporate demand endogenously, especially for innovative intermediate products. The rate of customer adoption of a product mainly impacts the demand. Because of this, the extension will be based on the famous Bass Diffusion model. Bass (1969) describes the process of how innovative products get adopted as an interaction between potential adopters and adopters. This adoption process can provide a structural explanation for demand development by incorporating two opposed mechanisms resulting in S-shaped growth dynamics. In the past, research has focused less on intermediate product adoption than on the adoption of end products. This work specially examines how the general concept of the Bass Diffusion model can be used and adjusted to explain adoption processes of intermediates traded at an intermediate level in supply chains that are used for end products. In the following paragraph is elucidated how the research objective is narrowed down to adoption processes of intermediates.

A supply chain consists of different echelons. For basic understanding, echelons can be separated into those which fulfill a delivery or storage function (distribution echelons) and echelons with a manufacturing function (production echelons). In regard to this, it is generally the case that for each product flowing out of a production echelon, several raw materials or other intermediates with lower net value, flow into these echelons (n:1 relationship) and are manufactured to create added value. In contrast to that, in the case of distribution echelons the product remains unchanged, so that the same product that flows into the echelon also flows out of the echelon (1:1 relationship). Furthermore, one main difference can be identified for intermediate products traded at production echelons within supply chains, in contrast to end products traded to the consumer end market at the end of supply chains. The main difference is that the trading environment changes from a business-to-consumer (B2C) setting to a business-to-business (B2B) setting. This alternation makes it complicated to adapt the Bass Diffusion model to adoption processes of intermediate products traded within supply chains, because the two general market mechanisms used in this model, word-of-mouth (WOM) and B2C-advertisment (B2CA), are conceivably not directly applicable to adoption processes of intermediate products that are traded at production echelons in B2B environments. In other words, if the focus lies on the diffusion of a product at the end of supply chains, the buying motives of the end consumers can be primarily taken into account in regard to the adoption process (influenced by WOM and B2CA). But the adoption process of intermediate products is first and foremost at the mercy of the buying motives of downstream production echelons and only indirectly dependent on the buying motives of the consumers at the end of the supply chains, who consume the end products containing the intermediate products.

To sum up, the Bass Diffusion model was designed for consumer products at the end of supply chains, as evidenced by the two included general market mechanisms WOM and B2CA. This research diverts the focus from the general B2C perspective to a B2B perspective. The research objective in regard to this is to examine, (1) weather these market mechanisms also take place for intermediate products within the chain and if not, (2) weather substitutable mechanisms for the two mentioned ones can be identified thus explaining the adoption processes in B2B settings. The operational goal in regard to these topics is to build a System Dynamics model that endogenizes demand of innovative intermediate products.

Research question: How is the Bass Diffusion model adaptable for incorporating endogenous demand of intermediate products traded at intermediate supply chain production echelons in business-to-business environments?

1.2 Introduction of Core Concepts

Supply chain: Stevens (1989, p. 24) defines a supply chain as “a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via the feed forward flow of materials and the feedback flow of information”.

Standard SCM: Widely used supply chain model which is based on the causal structure of the beer distribution game (Sterman, 2000, p. 688). This model can explain oscillation, amplification and phase lag of upstream demand and downstream supply. In the standard SCM the demand at the end of the supply chain in the form of incoming orders remains exogenous.

Distribution echelon: A single actor in a supply chain involved in moving a product or service from the supplier to the customer. Examples are: wholesalers or retailers.

Production echelon: A single actor in a supply chain who provides a product or service. Often these products are moved by distribution echelons to other producers or to the customer end market.

Demand endogenization: Identification of the causal structure with balancing and reinforcing mechanisms, which is determining dynamic demand behavior. In practice, entirely endogenization is never fully reachable. Simplified assumptions have to be made and the processes behind complex patterns and phenomena have to be abbreviated.

Bass Diffusion model (BDM): Bass (1969) developed a model which can explain diffusion of innovations. Originally, the model was introduced for forecasting sales of new products (Sterman, 2000). Three main mechanisms are included in the common System Dynamics representation of the model: advertising, word of mouth and market saturation. The resulting diffusion curve is S-shaped. The model is extendable and adjustable and is useable for demand endogenization, as the model can structurally explain demand driving mechanisms.

Innovators: Innovators are not influenced in their decision to purchase a product by the people who already adopted the product. In the Bass Diffusion model they are a function of the number of potential customers exclusively. (Bass, 1969)

Imitators: Imitators learned to some extent by interacting with those who have adopted the product already. This means they are influenced by the number of previous buyers and their number depends on the potential customers in the BDM upon and those who actually purchased. (Rogers, 1983)

Market saturation: The point at which a market is no longer generating new demand for a product. Taking into account the Bass Diffusion model, this point is reached, when all potential adopters of a product have become adopters.

Substitute: Equivalent product that can fulfill the same function for the customer. Products are substitutable to one another if the functional compatibility is fulfilled in the eyes of the customer.

2. Methodological Approach

In this research the focus is on developing a qualitative causal structure to incorporate demand endogenously, showing how this structure is applicable to a standard SCM model, and testing the developed framework quantitatively with a real-world case[1]. Hence, the research approach is predominantly deductive, because a structural theory will be developed first and then this causal structure is operationalized and tested with a real-world case. Since this test also gives an indication on the principal generalizability of the suggested demand endogenizing approach, the research has also inductive implications.

2.1. Research Strategy

Demand formation is a complex issue. This work aims to understand the macro behavior of demand formation in general and its application in a real-world context, thus to be able to draw general conclusions on how demand is determined by different quantifiable diffusion processes. To achieve this aim, a mixed research strategy is used in this work, so that different types of concepts are applied.

The development of the conceptual framework and the theoretical model is initially exploratory and is based on literature research. The focus is on existing theory about supply chain dynamics and the diffusion of innovations. The aim hereby is to understand the general causal mechanisms that are responsible for demand formation in regard to intermediates traded at intermediate levels in supply chains. The purpose of the literature research is hereby to find theories that explain and uncover these fundamental demand driving mechanisms. Furthermore, the conceptual framework needs to be connected to a standard SCM. Therefore, also discussion with different experts in the field is conducted to define how the extension is to be coupled. Structural validation involves in addition, testing the developed conceptual framework against a specific case.

For the development of a theoretical model that enables demand endogenization of innovative intermediate products, the following literature sources are used. Point of departure is literature about supply chain management (Beamon, 1998; Duggan, 2004; Forrester, 1961; Sterman, 1992, 2000). With regard to demand endogenization, the starting point is the original work from Bass (1969; 2004) and secondary literature about the Bass Model (Mahajan, Muller, & Bass, 1995; Senge, 1990; Sterman, 2000). Also work from Rogers (1983), Towill (1994) , Saeed (2009), Goodman, Kreutzer, Sterman, and Kreutzer (1993) and others will be taken into account for model construction. Discussions with two company partners and the university partner encompass the modeling process.

At the end of this paper, a systematic critical appraisal of the research follows in the last research phase. The critical review is structured into the following parts: summary and interpretation of research results, contribution to the knowledge base and managerial implications, limitations, critical review of omitted feedback processes and directions for further research.

2.2 Methodological Implications for Making Use of the Framework

The developed demand endogenizing framework was tested with a real-world case study from the nutrition industry. Involved company partners were Flostock BV (located in Eindhoven, The Netherlands) and DSM Food Specialties (located in Den Haag, The Netherlands). The full documentation of this part of conducted research is not provided in this paper due to a non-disclosure agreement. In the following are methodological implications outlined, to make use of the framework in regard to a case study.

The general structures shown in this paper need to be adjusted to the regarded case-specific situation. In every case study specialties in regard to specific demand drivers, need to be taken into account. This phase of research has explanatory implications and follows a case study approach as research strategy. The aim is to build a model based on the developed framework in order to form a dynamic hypothesis which can explain the case-study-specific problematic behavior. Semi-structured expert interviews are necessary, in which information is collected from the problem owning company partner(s). Interviews allow accessing the mental database of managers, who are closest to the necessary information. The reason for incorporating the mental data of experts with practical knowledge is to consider specialties of the regarded case-specific situation and to be able to validate the developed dynamic hypothesis. Furthermore, interviews make it possible to elicit

[1] Because of a confidentiality agreement, the conducted case study comparison cannot be fully documented.

information from the participants about available quantitative data sources (proprietary and public databases and other sources). Quantitative data can be basically gathered via archival research (including documents from company partners), via internet search or generated in expert interviews (educated guesses). With these interviews it is possible to validate the structure by examining, weather the incorporated feedback mechanisms are also deemed important from the firm perspective. A benefitting side effect of this procedure is increased commitment at the company by fostering a feeling of ownership from the company for the model.

3. Literature Research of Existing Theory

In this chapter an introductory literature review of the two key topics included in this paper is provided. If you are familiar with any of the described issues in this chapter, the recommendation is made to skip the corresponding subchapter(s).

In the first subchapter the management of supply chains with System Dynamics models is envisaged to give the reader a basic understanding of the fundamental matter. In particular, basic structures and dynamics of supply chains are discussed. This first part ends with an introduction of the Beer Game, as a wide-spread management introduction in respect to supply chains. The second subchapter deals with diffusion concepts which enable to endogenize demand formation for products. For this purpose, diffusion models are reviewed from existing theory. Especially the later used core component of the theoretical model, the Bass Diffusion model, is reviewed and visually depicted. Furthermore, specialties in regard to the diffusion of intermediate products will be discussed and linked to existing theory at the end of the chapter.

3.1 Supply Chains

Supply chain modeling is a diverse and widespread topic in the System Dynamics literature. Several scholars have worked out a huge variety of System Dynamics models to represent and capture dynamics within supply chains. These developments were initiated by the famous work from Forrester (1961): Industrial Dynamics. An overview about the evolution of System Dynamics in supply chain management is provided with the work from Towill (1994), Akkermans and Dellaert (2005) and Bhatti et al. (2012). In the next part an overview about this topic is provided to the reader.

Sterman (2000) points out that a supply chain consist of (1) the stock and flow structure to represent the supply line and (2) the management policies governing the flows of the structure. He emphasizes that the structure of a supply chain can capture a physical product such as an automobile (manufacturing supply chain), as well as the provision of a resource as skilled labor (labor supply chain) or an immaterial objectification such as product design (intangible product supply chain). This paper focuses on manufacturing supply chains. Forrester commented in regard to manufacturing supply chains: “A recurring problem is to match the production rate to the rate of final consumer sales. It is well known that the factory production rate often fluctuates more widely than does the actual consumer purchase rate. It has often been observed that a distribution system of cascaded inventories and ordering procedures seem to amplify small disturbances that occur at the retail level.” (Forrester, 1961, p. 21 f.) Figure 1 illustrates the physical production-distribution system, nowadays relabeled as manufacturing supply chain (Akkermans & Dellaert, 2005). Two flows run in the opposite direction. Orders, as information flow, are passed in upstream direction through the chain, while goods, as material flow, are delivered in downstream direction.

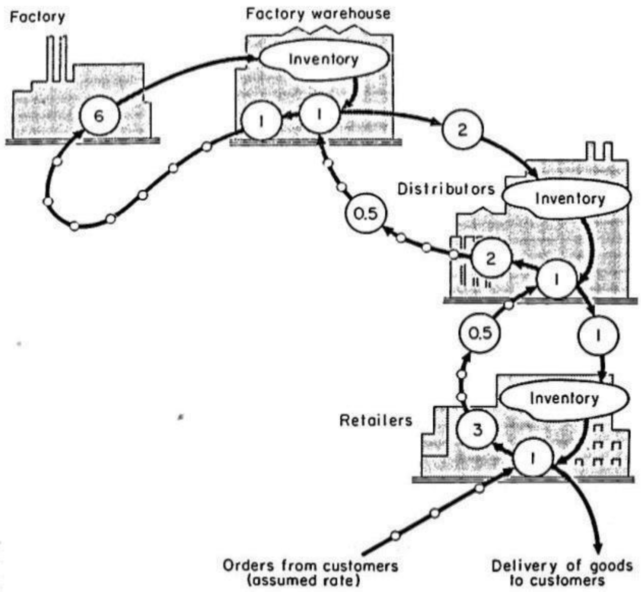

Figure 1: Organization of the production-distribution system. (Source: Forrester (1961, p. 22))

In the next section structures of and behavior in supply chains are discussed in that depth that is necessary to provide a sufficient grounding of the topic in regard to the research objective of this work. Chapter 17 (Supply Chains and the Origin of Oscillations) and Chapter 18 (The Manufacturing Supply Chain) from Sterman (2000) are especially good sources to start to get more information in great detail.

3.1.1 Structures to Represent Supply Chains

In general terms, a supply chain consists of a sequence of different echelons connected through a forward flow of materials and a backward flow of information (Stevens, 1989). At the highest level of generalization, a supply chain contains two integrated basic processes: (1) the process of production scheduling and inventory control and (2) the process of distribution and logistics (Beamon, 1998). In view of this and as stated in the introduction at the beginning of the paper, production echelons can be distinguished from distribution echelons[2]. An example of a multi-stage supply chain system is provided with Figure 2.

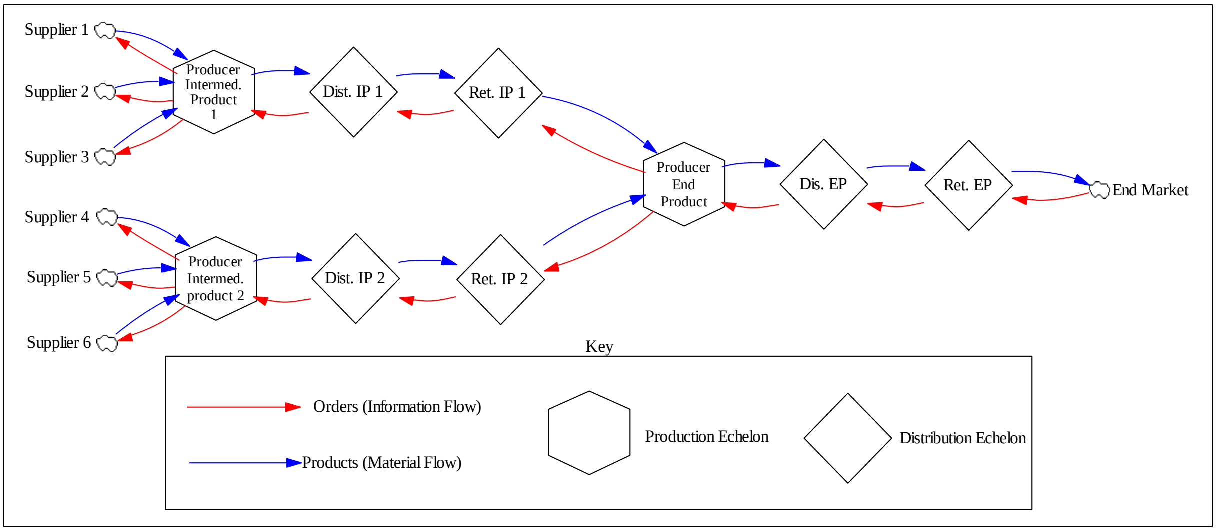

Figure 2: Example of a multi-stage supply chain with three combined single-stage supply chains (the first two are coupled to the last one).

Several suppliers distribute materials to two producers. Each of them manufactures an intermediate product. The intermediate products are shipped via distributors and retailers to the downstream producer of the end product. This end product is shipped to the end market via another distributor and another retailer. In reality these production-distribution systems are much more complex and span up whole supply chain networks (Beamon, 1998).

Two generic structures are sufficient to model supply chains with System Dynamics. One generic structure represents a distribution and the other structure represents a production echelon. Indeed, this distinction is also implicitly made by Sterman (2000) with figure 18-2 (Sterman, 2000, p. 711) and figure 18-5 (Sterman, 2000, p. 715). Sterman discerns between order fulfillment and production. While a distribution echelon consists of an order fulfillment structure only, a production echelon consists of a production scheduling structure coupled to an order fulfillment structure. The latter is the case because a production echelon also includes an inventory (called factory warehouse inventory in Forrester’s model). In other words, a production echelon is an extended distribution echelon. In the following section, the generic structures of production echelons and distribution echelons are described.

Figure 3 shows the generic policy structure of a production echelon. Production materials are delivered by suppliers via a **Production Materials Rate**. The **In Production** stock represents the amount of products which are manufactured in the production facilities. Finished manufactured products flow out of these facilities via the **Production Rate** into the **Inventory** of the producer. The **Shipment Rate** from this inventory is at the mercy of an **Order Fulfillment** subsystem. Order fulfillment is dependent on **Incoming Downstream Orders** and the amount of products in the inventory. Orders that are made by downstream echelons are dependent from

[2] The terms production and distribution echelon are also used in the literature, compare with J. F. Williams (1981) and Ibrahimov, Mohais, Schellenberg, and Michalewicz (2012)

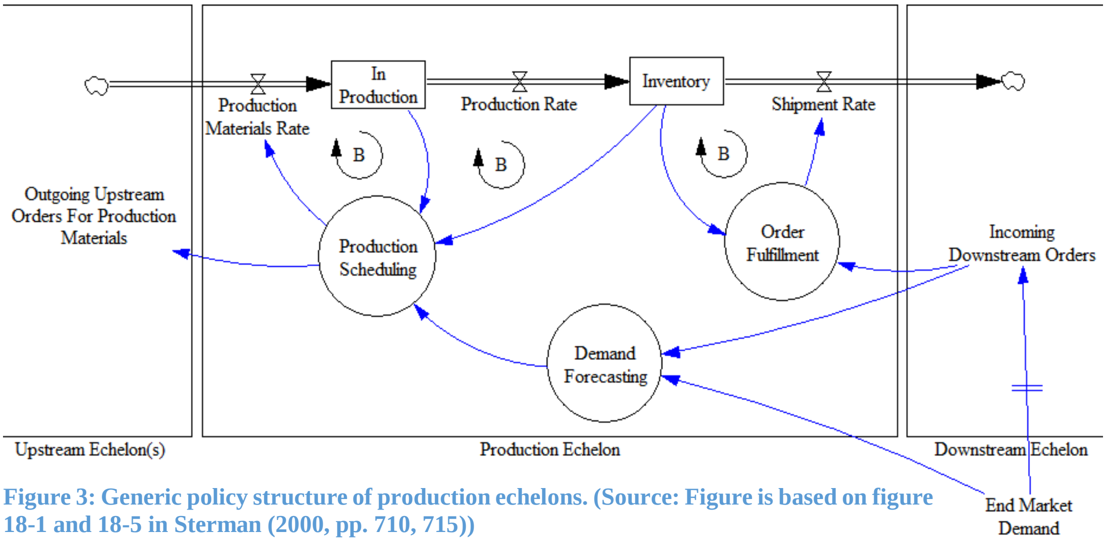

Figure 3: Generic policy structure of production echelons. (Source: Figure is based on figure 18-1 and 18-5 in Sterman (2000, pp. 710, 715))

the **End Market Demand** and oscillating demand magnification caused by the bullwhip effect (note the delay mark). Downstream orders, together with the end market demand, are fundamental input for the **Demand Forecasting** subsystem. The forecasted demand together with the amount of products in production and in the inventory are the basis for the **Production Scheduling** process that determines how many **Outgoing Upstream Orders For Production Materials** are sent to one or several upstream echelons. Finally, it is pointed to the fact that all the loops are balancing ones. Balancing loops are characteristic for supply chains (Sterman, 2000).

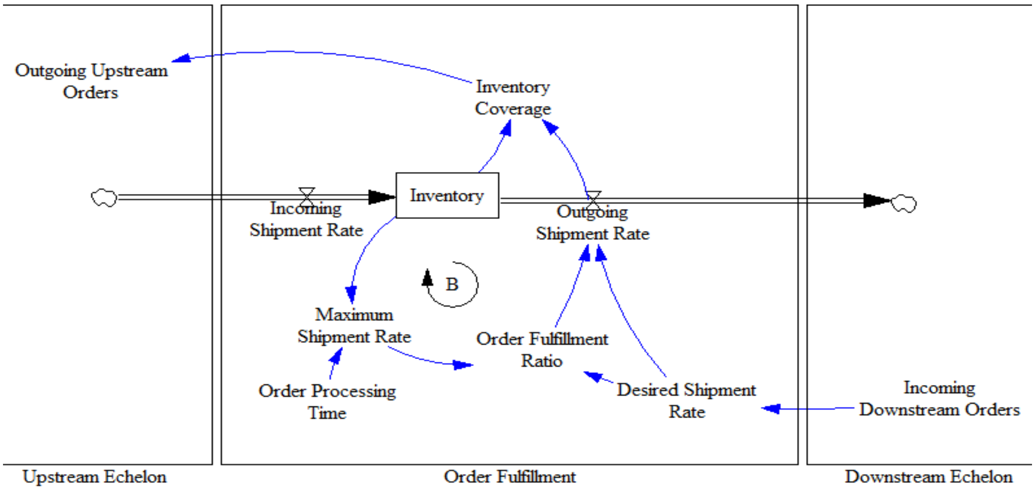

Figure 4: Simplified generic structure of distribution echelons. (Source: Figure is based on figure 18-2 in Sterman (2000, p. 711))

In Figure 4 the simplified generic structure of a distribution echelon is shown. This structure is also included into the structure of production echelons, because the producer also possesses an inventory. Indeed the structure is the disaggregated order fulfillment subsystem of Figure 3. The structure is kept very simple, excluding backlogged orders. The **Inventory** stock is the central element in the structure, with the **Incoming Shipment Rate** as inflow and the **Outgoing Shipment Rate** as outflow. The echelon is connected to the upstream echelon via **Outgoing Upstream Orders** and the incoming shipment rate and to the downstream echelon via **incoming Downstream Orders** and the outgoing shipment rate. The other auxiliary variables under the inventory in the figure are used for the order fulfillment calculation. The outgoing shipment rate is dependent on the **Order Fulfillment Ratio** and the **Desired Shipment Rate**. Latter variable is determined by the incoming orders. In this simple model the assumption is embedded that orders which cannot be fulfilled are lost. Consumers seek other sources of supply in such a case (Sterman, 2000). If the amount of units in the inventory is sufficient, the requested orders are shipped and removed from the inventory. The order fulfillment ratio is used for this purpose by calculating the ratio of the **Maximum Shipment Rate** over the Desired Shipment Rate. The amount of products in the inventory together with the order processing time determines the maximum of shippable products. Finally, if the **Inventory Coverage** decreases, new orders are placed.

In this work more details about other features of conventional supply chain structures are out of scope. Both shown figures should be seen as introducing System Dynamics structures into supply chain modeling to provide a basic understanding to the reader. Recently, several authors still improve these structures to incorporate better mechanisms for forecasting in regard to the dynamics in supply chains (see for example Burridge (2011), Saeed (2009) and Yasarcan (2011)). In the following are the resulting dynamics within supply chains elaborated.

3.1.2 The Beer Game Supply Chain

A generic descriptive manufacturing supply chain representation (defined as standard SCM in this work) is available with the so called Beer Distribution game. This simulation game is widely used in the literature to describe and illustrate the counterintuitive dynamics within supply chains (e.g. Senge (1990), Goodman et al. (1993) and Duggan (2004)). The game includes one production echelon and three distribution echelons.

Figure 5 shows a visual depiction of the Beer distribution game. In brief, four different echelons

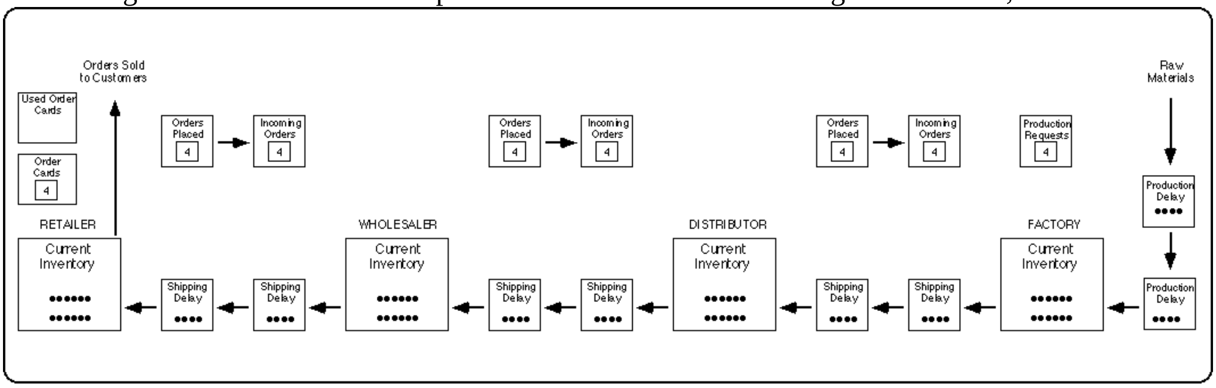

Figure 5: The Beer Distribution game. (Source: Sterman (1992))

(retailer, wholesaler, distributer and factory) are building up the supply chain. Between those echelons chips, understood as beer units, are ordered and shipped with an order processing delay of one time step and a shipping delay of two time steps. The players of the game manage the different echelons separately with the individual goal to keep costs low. Costs arise by holding beer as inventory and by delayed delivery, in case the inventory stocks are empty. Latter backlog costs are twice as big as former inventory costs per unit and time step. The decision on how many units are kept in each inventory is managed by the players individually. Each player just receives the information about how many new units are ordered by the downstream echelon (information flow) and how many units arrive from the upstream echelon respectively the stock of raw materials (malt, hops and yeast) for the last factory echelon (material flow) in compliance of the delay times. The incoming number of orders of the first retailer echelon remains exogenous and is given by a stock of cards.

Lessons from the Beer Game

Figure 6 shows typical results of the simulation game. Three characteristic patterns can be identified in these graphs: oscillation, amplification and phase lag. Oscillation is arising from the varying exogenous input and the significant time delays in the game. Players' orders and inventories chronically over- and undershoot the appropriate levels due to the delayed arrival of orders and units. The graphs show that the under- and overshoots are amplified in upstream direction of the supply chain. At each echelon in the chain – from the retailer to the factory – the fluctuation amplitude increases, because it takes longer for the demand information to flow through the chain. The consequence is that production fluctuates more than consumption. Another characteristic behavior is the tendency that the order rate peaks later with the move from the retailer to the factory. This phase lag pattern is also at the mercy of the involved delays.

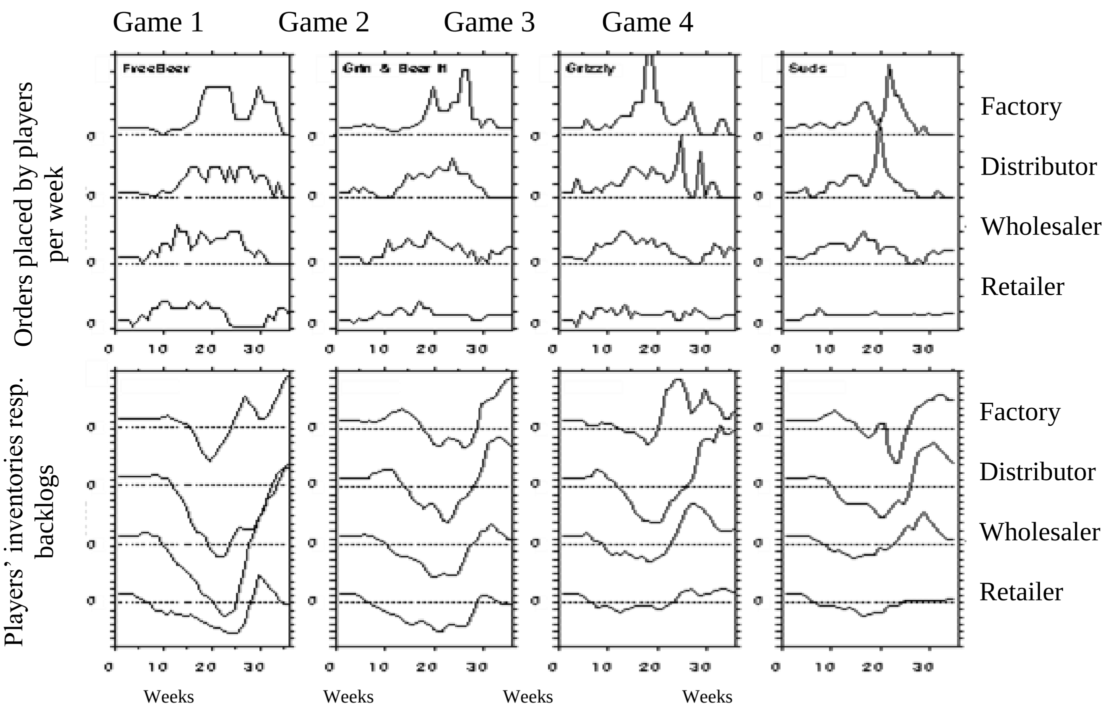

Figure 6: Examples of typical game results. (Source: Sterman (1992))

3.1.3 Generic Dynamics within Supply Chains

The bottom line of the described dynamics is the oscillating demand magnification upstream effect. This effect was first explained in Forrester's book *Industrial Dynamics* and is nowadays labeled as bullwhip effect or Forrester effect (Towill, 1994). A generalized representation of this effect is shown in Figure 7.

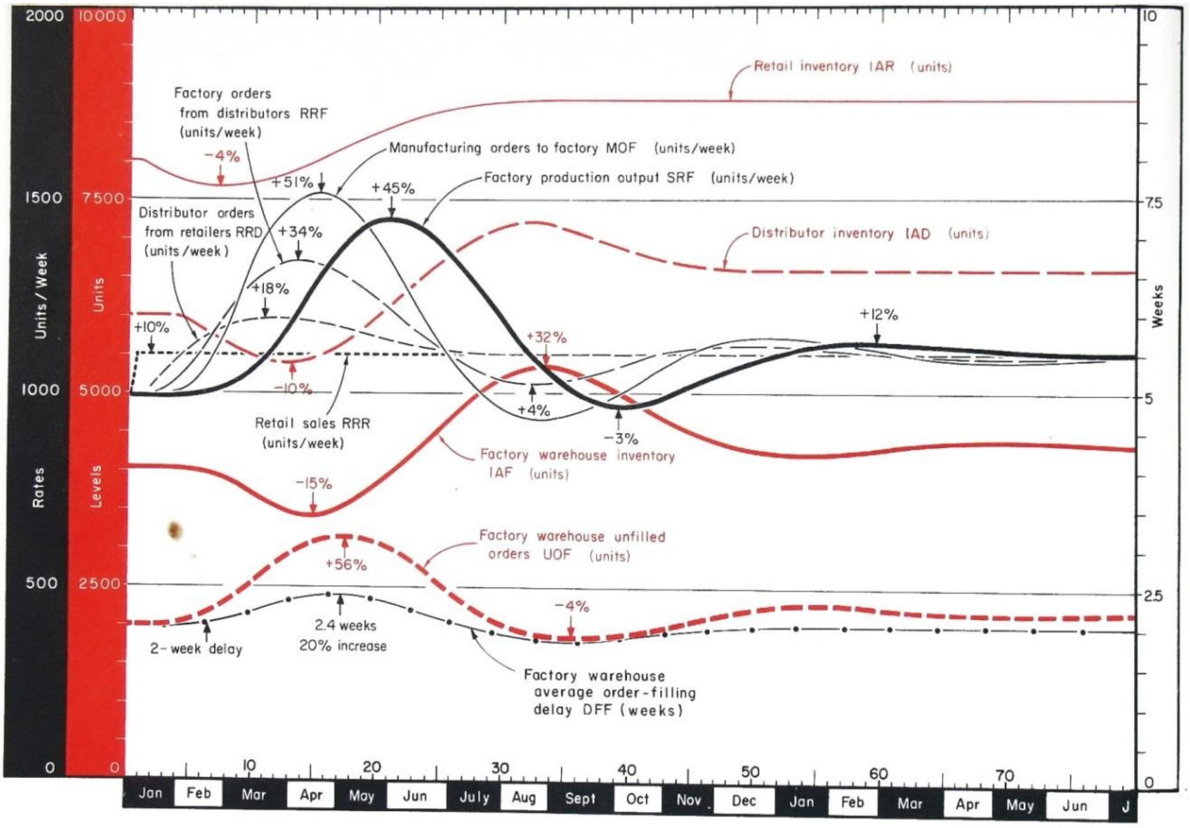

Figure 7: Response of the production-distribution system to a sudden 10% increase in retail sales. (Source: Forrester (1961, p. 24))

The fluctuation of order rates, inventories, factory output and unfilled orders in this diagram is the result of a simple exogenous 10 percent step increase in retail sales. It is graphed how the generic production distribution system (see Figure 1) reacts on such a simple disturbance. Forrester explains the disturbances with a System Dynamics structure of a cascade of inventories, modeled as stocks, and flows between these inventories (in his structure no distribution echelon is included). The increasing amplifications from the retailer via the distributor to the factory are primarily caused by time delays in the model structure, similar to the behavior observed in the Beer Game. After this quick introduction into the dynamics and the structures of supply chains, the next subchapter focuses on the diffusion process of innovative products.

3.2 Product Diffusion in Respect of Demand Endogenization

Demand is defined as the quantity of a product people are willing to buy (Whelan & Msefer, 1996). The demand of a product stems from the diffusion of a product into the market and by diffusion processes within the market (Duval & Biere, 2002). Diffusion models provide a structural explanation on how demand is expected to develop over time (Sterman, 2000). Under regular circumstances, demand of an innovative product increases in the beginning through information spreading, but stops to increase after a while through market saturation processes. Because of the importance of diffusion processes for demand endogenization, it is essential to ground the work on a reliable diffusion concept. The incorporated diffusion concept in this work, to describe and model adoption respectively diffusion processes[3], is the Bass Diffusion model (BDM). In the late 1960s Frank Bass developed a "new product growth model for consumer durables" (Bass, 1969). Bass' put mathematics behind the theory from Rogers (1962) on the diffusion of product innovations (Ambroz, 2009). Hence, this model enabled to describe mathematically S-shaped growth dynamics of diffusion processes in general and to forecast sales of new products in particular. The dynamics which are explainable with the BDM are very close to the diffusion patterns of diseases. Latter ones are covered in so called epidemic models. A short introduction into these kinds of models is provided in the following before the BDM is elaborated.

3.2.1 An epidemic diffusion model

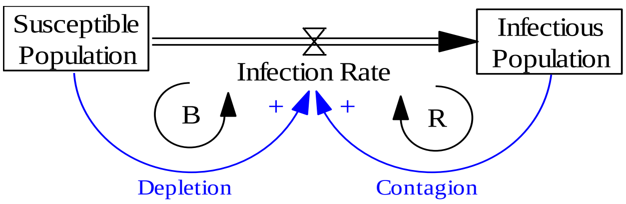

Figure 8: Simple epidemic model.

Figure 8 illustrates a simplified version of an epidemic model. Basically, there are two stocks in the simple versions of these kinds of models. One stock described as **Susceptible Population** and one stock named **Infectious Population**. Between these two stocks a flow from the susceptible to the infectious population, called **Infection Rate**, is determined by depletion and contagion processes. Depletion occurs when the individuals that can be infected become scarcer. While depletion is at the mercy of the susceptible population and is higher if the susceptible population is bigger, contagion is dependent on the infectious population and increases with the size of the infectious population. Hence, the two processes are opposed mechanisms which determine the rate of infection over time. The infection rate (see left-handed diagram of Figure 9) is low in the beginning, because there are only a few infected individuals which can infect others. After a while more individuals get infected and thus the infection rate increases. At some point the infection rate reaches a maximum and decreases afterwards, because there are not enough uninfected individuals that can be infected by the

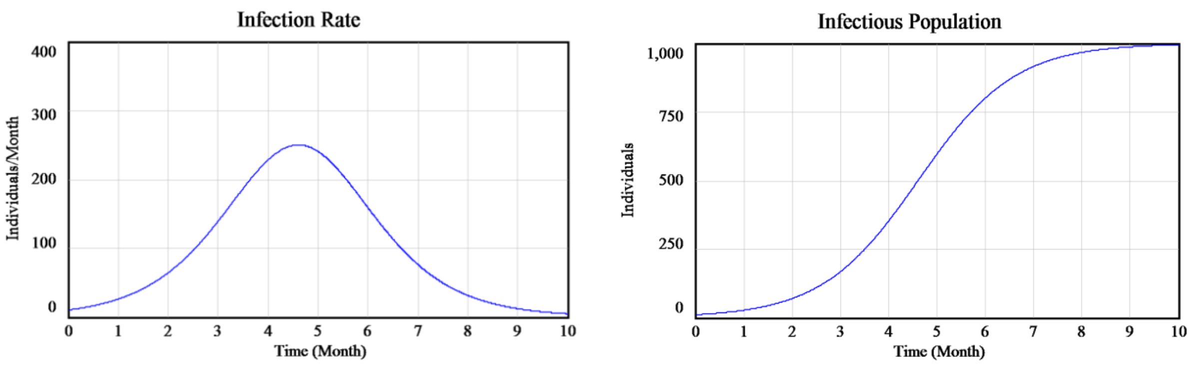

Figure 9: Infection Rate and Infectious Population over time.

[3] In diffusion theory the concepts of diffusion and adoption are generally tantamount (Rogers, 1983).

infected population to hold the infection rate up. The consequence is a falling infection rate. The curve for the infection rate shows a logistic distribution function, known as logistic probability density function. And the curve of the infected population is the integral of this function, the accumulated number of infected people over time (see right-handed diagram of Figure 9), is S-shaped. This curve is called a cumulative distribution function.

3.2.2 The Bass diffusion model

Similar dynamics such as the ones described above are fundamental in System Dynamics representations of the BDM (see Figure 10) with the difference of changed terminology for the stocks and the driving mechanisms. Instead of the stocks susceptible population and infectious population, the two stocks potential adopters and adopters are used and the infection rate is named adoption rate.

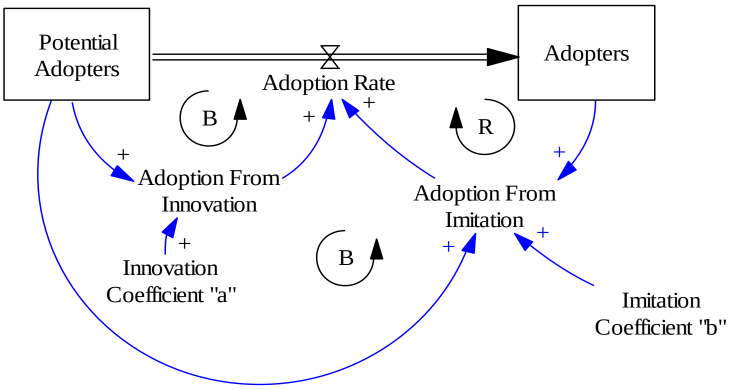

Figure 10: System Dynamics representation of the Bass Diffusion model based on the original equation.

In the original Bass model[4] the names of the two driving mechanisms haven't been specified at the operational level (Sterman, 2000). Bass named them in a generic fashion innovation and imitation (similar to depletion and contagion in the epidemic model). While innovation is at the mercy of the amount of potential adopters that starts using a product without a dependency on how many people already adopted the product, imitation takes into account these spillover effects which describe that people are more willing to adopt an innovative product if many people have adopted the product before. Sterman (2000) points out, that others refer to them as external (= innovative) and internal (= imitative) influences. Another possibility is to refer to them as push and pull adoption, because one mechanism is at the mercy of the pushing potential adopter population (similar to innovation and external adoption) and the other one is dependent from the pulling pool of adopters (similar to imitation or internal adoption).

In contrast to these general expressions mentioned above, also more specified names are used in System Dynamics representations of the BDM, to provide a better defined and pictorial understanding of the mechanisms to readers. In most SD illustrations of the BDM the terminology *adoption from advertising* and *adoption from word of mouth* is incorporated. These two traditionally incorporated effects make more sense in a B2C than in a B2B setting. This point is covered later on again. It is already anticipated that regardless of the names which are given to these effects, it's essential to understand that the incorporated name-giving effects (as the ones from above) are always overestimated, because all other not mentioned effects are omitted together with the fact that the innovation and imitation parameters are calibrated[5] in a way to have a smooth fit to the past development. To make this more clear: If only the reinforcing mechanism adoption from word of mouth is incorporated, other reinforcing mechanisms like adoption from hot product perception or adoption from increasing media reports are omitted if not made explicit in the model and the only incorporated mechanism is overestimated as the parameter influencing this mechanism is chosen to fit the data.

The behavior of the BDM is shown in the phase plots[6] (Figure 13 to Figure 11). In the first phase plot adoption from innovation is cut-off. In the second one adoption from imitation is cut-off. And in the third one both sources of adoption are active. The initial adopter population was set to 1/100 of the total population. Otherwise, if the initial adopter population is set to zero and adoption of innovation is cut-off, no adoption would take place. The two important lessons from these phase plots are: (1) Early adopters are generated by the adoption from innovation and are highly responsible to reach the kick-off point quickly and (2) in the long-run the bigger amount of adopters is normally generated by adoption from imitation for conventional parameter settings.

[4] The original Bass model did not incorporate a feedback structure. The model was primarily based on the following equation: $\frac{d\ Adopters}{d\ t} = Adoption\ rate = a \cdot Population + b \cdot Potential\ adopters$
with a as innovative parameter and b as imitative parameter (Bass, 1969).
[5] Bass (1969) proposed regression analysis using time series data to ascertain values for both parameters.
[6] Answer to the challenge *Phase Space of the Bass Diffusion Model* in Sterman (2000, p. 333)

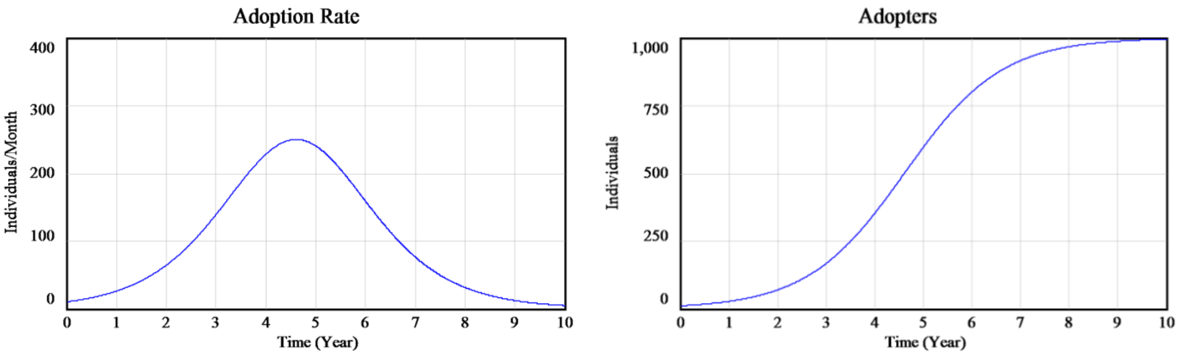

Figure 13: Adoption from imitation is only active.

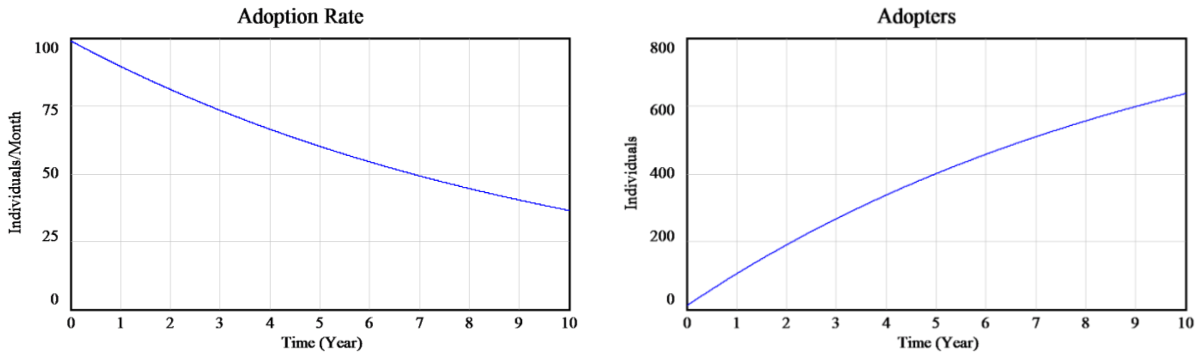

Figure 12: Adoption from innovation is only active.

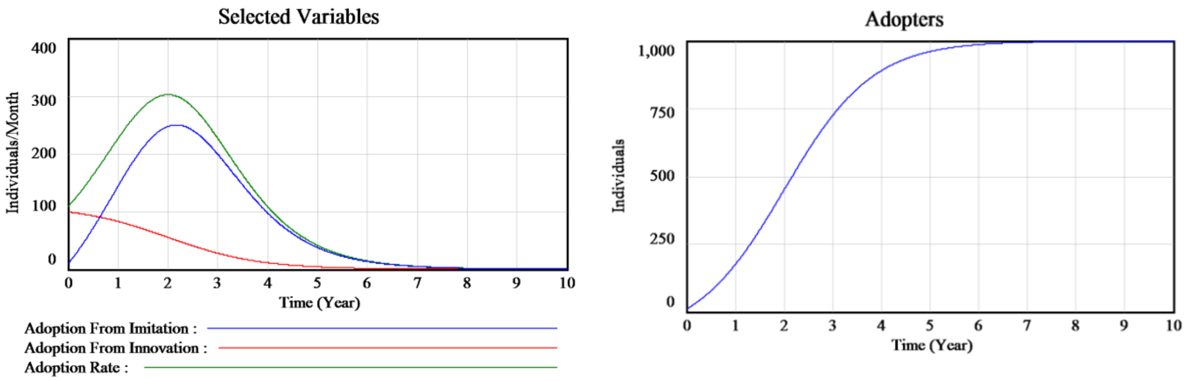

Figure 11: Both adoption processes are active.

The Bass model is very wide-spread in academic literature[7] and was also incorporated into many System Dynamics models (see for example Groesser, Ulli-Beer, and Mojtahedzadeh (2006), Wunderlich and Größler (2012) and Strohhecker (1994)). Bass (2004) ascribes the success to the fact that the main output variable is of key interest to managers. As the model was developed especially to estimate the uptake of new innovative products, it provides in regard to the research objective, a good starting point for a model structure to incorporate endogenous demand. But the pattern generated by the BDM remains just an empirical generalization (Mahajan et al., 1995) and for specific cases the model needs to be modified (Bass, 2004).

3.2.3 Specialties for Intermediate Product Diffusion

The aim is to make use of the Bass Model for the development of a theoretical model that incorporates endogenous demand of intermediate products. For this purpose it is necessary to examine characteristics of the diffusion of intermediate products compared to those of end products, and thus whether the Bass model needs to be adjusted in regard to these particularities. In this subchapter these specialties are examined. Later, when the theoretical model is discussed, they will be taken up again.

[7] It is referred to be one of the ten most frequently cited papers in history of management science (Moxnes, 2009).

A major difference is fundamental in regard to the diffusion of intermediate products. The systemic alternation is that intermediate products are sold to other producers while end products are sold to consumers[8] at the public market. In other words, the business environment changes from B2C (business to consumer) for end products to B2B (business to business) for intermediate products. In general, the volume of B2B transactions of intermediate products and raw materials is much higher than the volume of B2C transactions of end products sold to end users (Shelly & Rosenblatt, 2011). The reason for this is that each B2C transaction generally involves many B2B transactions. For example a food producer has to make many B2B transactions (buying ingredients, machines, packaging material as well as transactions concerning production facilities, transportation and so on) first, before he can sell a product like an instant meal to the consumer. To describe this circumstance from the perspective of a product: a product like an instant soup has gone through several value-adding B2B processes in which different industries have been involved, before it is sold to the end user in a single B2C transaction. In the next section differences between both types of transactions are reviewed based on Ellis (2010).

The volume of a single B2B transaction is normally much higher than the volume of a single B2C transaction in regard to both, the size of orders and the value of orders. The consequence is that B2B transactions are riskier, because of the higher investment sums. Ordering the wrong quality or quantity, agreeing on too expensive payment terms or simply buying the wrong product or service can imply high threats for a business. The consequence is that greater expenditures are made to assess these risks better. These risen transaction costs are reflected by more meetings between buyers and sellers, probably requiring prototypes or samples of the product for the buyer, together with the fact that more individuals are normally involved in the decision making process. On the one hand, more involved people may handle more information to make better decision, but also decision making in groups is often more difficult and takes longer. Because of all aforementioned circumstances businesses tend to be more conservative concerning brand relationships and therefore brand loyalty tends to be higher in B2B environments. In Figure 14 the main differences between B2C and B2B buying behaviors and characteristics are distinguished. Which inferences follow from the described intermediate product specialties will be discussed in chapter 4.

Behaviours & characteristics	Consumer buying	Organizational buying
Number of buyers	Normally large	Normally small
Size of orders	Small	Large
Value of orders	Normally low	Normally high
Evaluating criteria	Social, ego, & utility	Price, value, & utility
Purchase initiation	Normally self	Normally others
Level of risk	Low to medium	Medium to high
Complexity of decision	Low to medium	Medium to high
Information search	Normally short	Normally long

Figure 14: Broad differences between B2C and B2B buying behavior. (Source: Ellis (2010, p. 39))

4. Conceptualization of the Demand Endogenizing Extension

The three major issues that have an impact on the demand development of products are (1) demand amplifications caused by delays and stock building in supply chains, (2) the progress of product adoption in regard to substitutes with the same or a similar function and (3) market trends of the submarkets of which the product is part of. Latter trends are – as will be elaborated – also at the mercy of various nested macroeconomic shifts[9] that are structurally similar to diffusion processes[10]. Being able to incorporate (1), (2) and (3) is the key to endogenize demand of end products traded to consumers at the public market and also of intermediate products traded to other producers. While (1) mainly influences short-term demand development, (2) and (3) are responsible for long term demand development. The conceptualization focuses on the latter two issues.

The conceptual idea is to aggregate all relevant adoption processes which determine product-specific demand curves. The realization of this idea is based on a three-step approach. Firstly, the product diffusion hierarchy, in which the adoption processes are nested, needs to be identified and visually represented. Secondly,

[8] Consumers can be also businesses that order from the public market.
[9] E.g. market share shift between several producers or shift in regard to the consumption volume of different submarkets.
[10] These shifts are also referred to as adoption processes.

a theoretical model is needed that can structurally endogenize adoption processes in a more specific way than the BDM, but remains general enough to be usable for different adoption processes[11]. And thirdly, a guideline is necessary that describes how the theoretical model is iteratively reusable at several different diffusion interfaces and that shows how the whole structure is to be coupled with the SCM. In the next paragraph the construction of the product diffusion hierarchy is elaborated on. Afterwards a conceptual model is presented in regard to point two and three[12].

4.1 Hierarchical Aggregation of Diffusion Processes

Pifko (2009) describes a strategic business segment as a market in the market, which is characterized by different buyers, different competitors and different supplied products. If such a strategic business segment is subdivided by the kind of supply it is called a submarket[13]. Each product is part of several nested submarkets, but also submarkets are part of other submarkets.

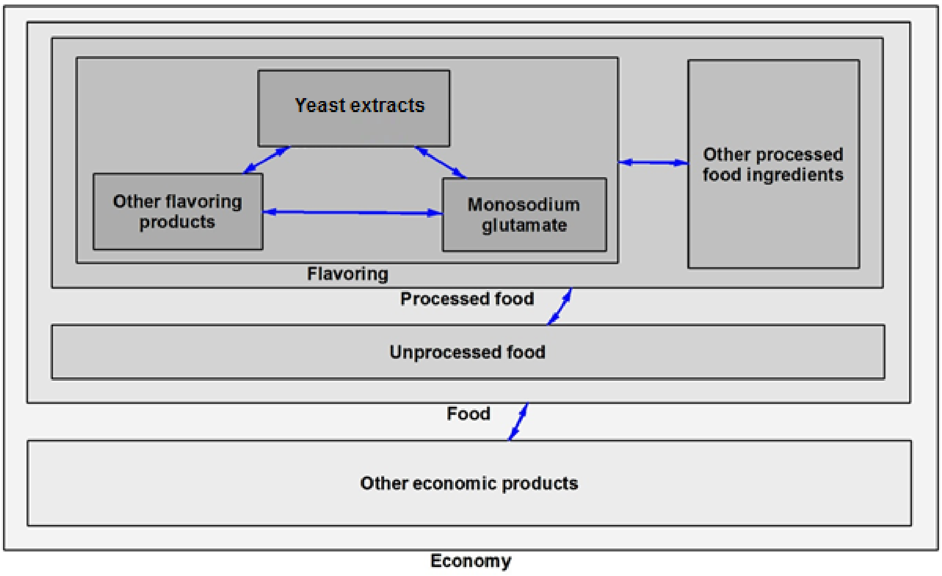

Figure 15: Hierarchical nesting of several adoption processes for an example case.

Shifts, as a result of adoption processes, occur between the demand volumes of products in the same submarket and between the aggregated demand volumes of different submarkets that are embedded in the same more general submarket and of the same hierarchical order. The hierarchical order of a submarket is dependent on the number of surrounding nesting levels. Incorporating endogenous demand is then about capturing these shifts respectively diffusion processes and about aggregating them in a logical way. The adoption processes are hierarchically nested as shown for an example case in Figure 15. Each double-headed arrow represents an adoption process and a box represents a submarket. Products are embedded in the boxes of the innermost submarkets. At the lowest level, a shift between the products occur (e.g. different concrete yeast extract products). At the second level, a shift between yeast extracts, monosodium glutamate and other flavoring products takes place. At the third level a shift between flavoring products and other processed food ingredients may occur, and so on. Adoption may not occur between all products and is also not automatically taking place between submarkets of the same hierarchical level. The outermost economic frame represents the maximum (sub-) market scope. The growth and decline of submarkets, respectively the adoption processes between submarkets, is at the mercy of various specific drivers. For example, the submarket processed food may be dependent on the percentual share of people living in urban areas. And so, if the volume of processed food increases the assumption is that automatically the share of all submarkets in the processed food market increase proportionally. It's possible to take into account another level in addition to the hierarchical nesting. Between the demand volumes of different producers also shifts occur. These market share shifts are nothing more than aggregated adoption processes between specific products.

In summary, product adoption processes impact (1) the demand volume of different products (e.g. different types of yeast extracts), (2) the demand volume of different producers (e.g. yeast extracts from one company versus yeast extracts from a competitor) and (3) the demand volume of different submarkets (e.g. yeast

[11] A further requirement is the applicability of that model especially for adoption processes in B2B environments.
[12] The whole developed theoretical model will be described in part 5.
[13] In contrast to a market segment that is subdivided by demand groups.

extracts versus monosodium glutamate). Each nesting level which is taken into account is named a diffusion level. Which diffusion levels should be taken into account in regard to a case study is dependent on the specific case context and also on data availability constraints.

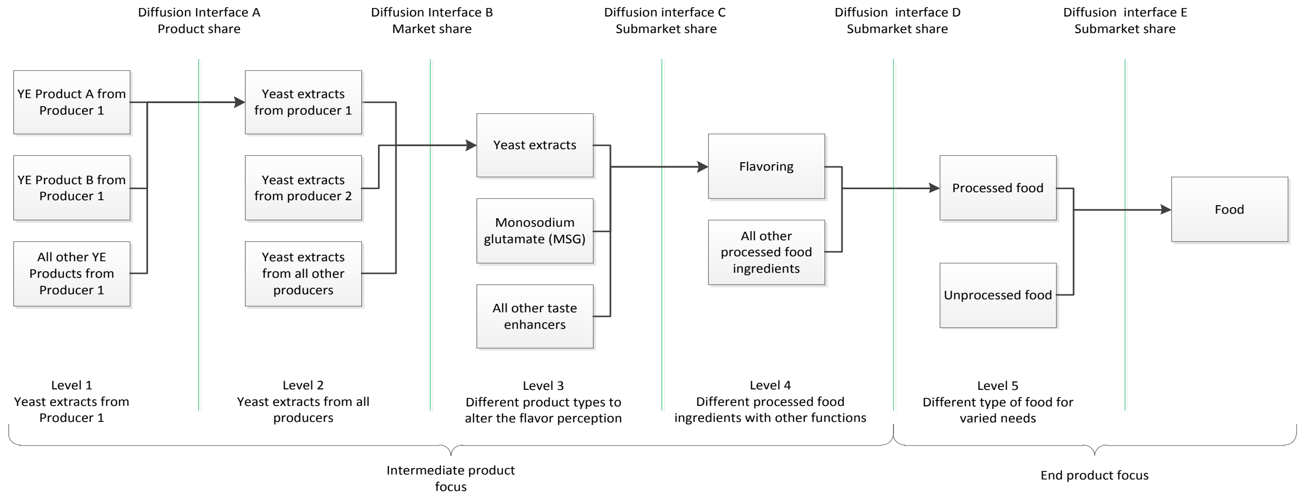

Figure 16: Diffusion interface hierarchy for an example case.

Figure 16 shows a diffusion interface hierarchy in regard to the case study. The figure extends the concept from Figure 15 because not only products (level 1) and submarkets (level 3-5) are considered, also producers (level 2) supplying products of similar type are taken into account. The shown hierarchy is just one possible representation, because indeed also more or less diffusion levels could be considered. That depends on how narrow or broad submarkets are defined. If no data is available for one level or if it is assumed that the overall adoption progress at on diffusion interface is not relevant respectively remains zero, a level might also be skipped.

4.2 Specialties in Concern of Intermediate Products

To repeat, two issues are different concerning intermediate products. Firstly, intermediates are traded at an intermediate level in the supply chain. Hereby it is important to elaborate how the endogenous demand extension is coupled with the standard SCM. And secondly the trading environment changes from B2C to B2B. In regard to the diffusion model, it’s important to elaborate which adjustments need to be made to take into account this aspect.

4.2.1 Aspects of Coupling the Endogenous Demand Model to the Standard SCM

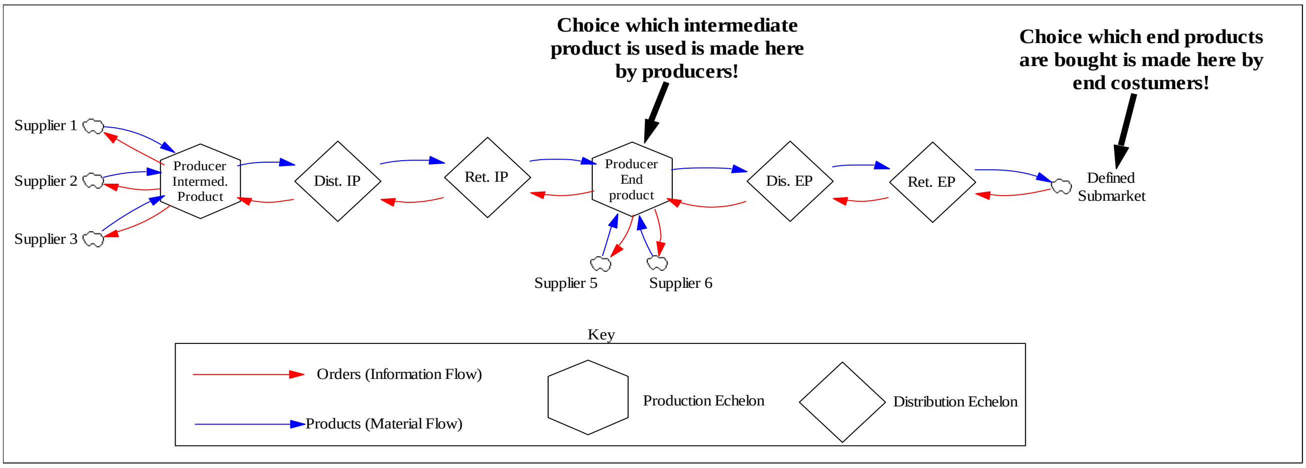

Figure 17: Simplified supply chain of the yeast extract distribution.

Figure 17 illustrates a simplified version of the supply chain. An intermediate product is produced at the beginning of the supply chain, remanufactured by an end product producer at an intermediate level in the chain and sold to a defined submarket at the end of the supply chain. In detail from left to right, several suppliers ship raw materials and other intermediate products to a producer who is manufacturing an intermediate product.

This product is then shipped via a distributor and a retailer to an end product producer who manufactures the end product. Also other raw materials and intermediate products which might be used for the end product are delivered. Via distributors and retailers the product is finally shipped to consumers of the submarket in which the product is sold.

In this chapter, it was initially stated that demand of an intermediate product is dependent on how fast the product is adopted by buyers which choose between the regarded product and substitutes which fulfill a similar function on the one hand, and from diffusion processes in the submarket(s) in which the product is sold on the other hand. Regarding the purpose to incorporate demand endogenously, the difficulty is (see upper comments in Figure 17) that the first issue, the choice of end product producers which intermediate product is used, has an impact at an intermediate level in the chain. But the second issue, the choice which products including the intermediate products are bought by end costumers, concerns the end of the supply chain. That means the whole demand forecast enabling model needs to be split into two different parts and each part needs to be coupled at a different point to the standard SCM. In other words, both issues need to be separated from one another, because adoption of intermediate products occurs within the chain and consumer end market trends trivially influences the end product consumption (at the end of the chain). This matter is discussed in subchapter 4.3 where the conceptual framework is elaborated.

4.2.2 Aspects of Intermediate Product Diffusion

First of all, the decision which intermediate product is used in an end product is made by the end product producers. It is assumed that end product producers choose intermediate products which can maximize the performance, as ratio of aggregated attractiveness indicators and costs, to meet the wishes of consumers in the best possible way. Therefore, also consumers at the end consumer market influence the decision in a secondary way, as they determine the attractiveness of products by choosing the products of their liking. Nevertheless, the turnover of intermediate products is in the first place determined by decisions of end product producers as organizational business subjects[14]. End producer decision making in B2B environments differs from consumer decision making in B2C environments. In chapter 3.2.3 the main behavioral differences and other changed characteristics in regard to this systemic altering have been elucidated. To these count, among others, changed evaluation criteria from attributes like “social”, “ego” and “utility” to attributes like “price”, “value” and “utility”, plus increased information search, complexity of decisions, level of risk, value and size of orders (Ellis, 2010).

The remainder is now how to take the described changed economic circumstances in terms of intermediate products in the diffusion model into account. This question can be made clearer with the two following questions. (1) How can intermediate product performance be incorporated? (2) Which adjustments of the BDM are necessary?

(1) Initially it was stated that performance is dependent of the (aggregated) product attractiveness on the one hand and of the costs of a product on the other hand. The idea is to incorporate a cost-benefit consideration, as such trade-offs are also applied by businesses for making decisions (Goodwin & Wright, 2010). If the value of the cost-benefit offsetting increases, the number of producers which are principally willing to adopt the intermediate product also rise, so the assumption. The aim is to include a mechanism that translates the result of the cost-benefit value into the fraction of producers which are principally willing to adopt the product. In addition, the costs of a product might be reduced over time, if experience grows and economy-of-scale-effects emerge. A learning curve can capture this effect. The attractiveness of a product can be calculated via a multi-criteria analysis calculation that includes defined criteria and determined weights of these criteria. Multi-criteria analysis is a standard approach in terms of organizational decision making (Goodwin & Wright, 2010).

(2) Although the original BDM only includes the mechanisms innovation and imitation, in many System-Dynamics-based representations of the BDM the effect “advertisement” is included beside the effect “word of mouth”. It will be elucidated whether advertisement and word of mouth are good terms to represent the innovation and imitation mechanisms and if not which other terms can replace them.

[14] In contrast to individual business subjects who normally make the decision to buy the end products.

In regard to advertisement it seems useful to distinguish between B2C-advertisment and B2B-advertisement. B2C-advertisement of end products[15] can be found on television, on the radio, in newspapers, outdoor on billboards and at many other places and is often lifestyle-oriented or designed for special target groups to awake needs of consumers spontaneously (Ellis, 2010). Because of the different behavioral characteristics such marketing efforts, that aim to spontaneously spark impression, might not be successful in B2B settings, as producers tend to make more deliberated decisions (Ellis, 2010). The different evaluation criteria and the increased level of stakes and risks are reasons for that. So the goal of B2B-advertsiment (e.g. presentation at fairs, dispatching of promotion material) must be to make the product known and to set the product on the producer's list of possible candidates. The producer will still look for the best product and is less influenceable by skillful marketing only, but just if the producer knows about the specific intermediate product he might buy it. To conclude, advertisement takes also place in B2B settings and thus can remain in the model as term for the innovation mechanism. But advertising efforts will affect only those producers, which are principally willing to adopt the intermediate product based on the result from the cost-benefit offsetting.

Word of mouth (WOM) is defined as "interpersonal communication between individuals within networks that either explicitly or subconsciously identify preferences" (M. Williams, 2007, p. 4). The WOM effect leads to a secondary marketing effect for producers in regard to end products bought at the end costumer market. However producers normally do not communicate which type of intermediate products they use for their products to other producers, such that it is assumed that the WOM effect is less relevant in the B2B settings. But as described in chapter 3.2.2 other effects are subsumed with this explicitly stated positive imitative mechanism: e.g. increasing market visibility, increasing perceived product attractiveness or increasing market power. In conclusion, the term "hot product perception" is assumed to be the best alternative for replacing the WOM effect as explicit imitative mechanism and to summarize the mentioned reinforcing effects.

4.3 Conceptual Framework

The conceptual idea is to disaggregate all relevant diffusion processes, as shown in Figure 16, which determine product-specific demand curves. The advantage of incorporating the different diffusion levels is to improve the demand forecast. For this purpose, the aim is to build a theoretical model that is usable at different diffusion interfaces. The hierarchical nesting of several diffusion processes (see Figure 15) makes this use of the modularity principle possible. The advantage of such a reductionist approach is to limit complexity and to enable demand endogenization for different case studies. Another advantage is the possibility to replace one specific module at one interface against an improved and more advanced module. The use of modules requires specifying interface variables that define how modules are connected among each other and to the supply chain in concern to avoid compatibility problems. The realization of this idea is based on a three-step approach and summarized in a conceptual guideline at the end of this chapter.

The conceptual idea includes three steps, as follows. Firstly, a standardized way to represent a diffusion interface hierarchy is necessary. In chapter 4.1 an example for the DSM case was given. Based on this representation is a generic diffusion interface hierarchy is provided. Secondly, a theoretical model is needed that can structurally endogenize interface-specific diffusion processes. This structure needs to be more advanced than the BDM, but remains general enough to be reusable at different diffusion interfaces. Specialties of intermediate product diffusion, as discussed in this chapter, need also to be taken into account for building this model. And thirdly, a framework is necessary that describes how the theoretical model is iteratively reusable in concern of the several different diffusion interfaces and that shows also how the modules are coupled among each other and how the whole structure is to be coupled with the supply chain model.

[15] B2C-advertisement of intermediate products is much rarer, although the transaction volume of intermediate products is much higher.

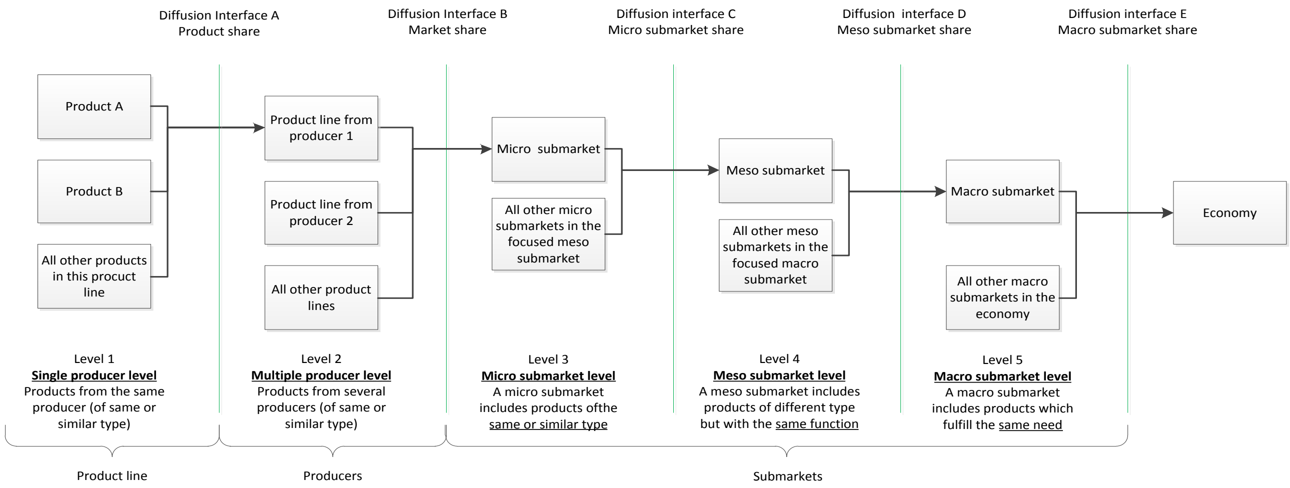

Figure 18: Generic diffusion interface hierarchy.

A generic representation of a diffusion interface hierarchy is given in Figure 18. The first level represents type-identical products from one producer. These different products can be aggregated as a product line[16] of a producer. The selling volume[17] of one product in comparison to the other products in the same product line is defined as product share and is therefore defined as diffusion indicator for level one. In general, diffusion indicators determine the percentual shift between the products in the different boxes at the same level. The different product lines of several producers are placed side by side at the second level. The diffusion indicator for the second level is the market share and captures the percentual market volume of one supplier in comparison to all other suppliers (but just in regard to products of the same type). At the third level all these products are aggregated in a micro submarket. Micro submarkets include type identical or type similar products. Next, the products from the micro submarket diffuse in a meso submarket. Products in a meso submarket can fulfill the same function for the customer. Products from different meso submarkets are aggregated in a specific macro submarket. Products in the macro submarket category fulfill the same need for the costumer. The corresponding diffusion indicator between submarkets is called submarket share. All macro submarkets together finally determine the whole amount of products accounted in the economy. The differentiation between the different submarkets is based on the economic terms product line, product class and product family (Pifko, 2009). The segregation between these groups respectively submarkets remains fuzzy and depends on the specific case under study. The split between intermediate products and end products is typically the diffusion interface among the meso and the macro submarket, because an intermediate product fulfills a function but normally cannot fulfill a customer need alone.

The theoretical model can structurally determine the diffusion process in regard to a single diffusion interface. How the model works will be discussed in detail in chapter 5. Important is that the model should be useable as module in a row of similar modules. These interlinked modules together define the demand curves of products, by aggregating the diffusion processes at the different interfaces. At this stage it is necessary to point out how the modules are connectable among each other and to the SCM. As it can be seen from Figure 18, the important interface variable between two levels is the “share variable”, specified for different levels as product share, market share or submarket share. This share variable will be the key output variable of the theoretical model and with that for each single module, describing the relative demand development. With this variable and an initial absolute demand volume, the absolute demand volume can be calculated over time. Share variables can be simply multiplied among each other to aggregate developments of several hierarchical levels. Furthermore, also a connection to the intermediate product specific SCM is possible with this variable. The incoming amount of all orders of the end product can be multiplied with the expected intermediate product-specific relative demand trend, to determine the amount of orders for the intermediate product in upstream direction of the supply chain. The next figure gives an illustration to this matter.

[16] A product line is understood as a pool of products supplied by a producer in a very narrow defined submarket.
[17] The selling volume can be measured monetarily or on a basis of sales units.

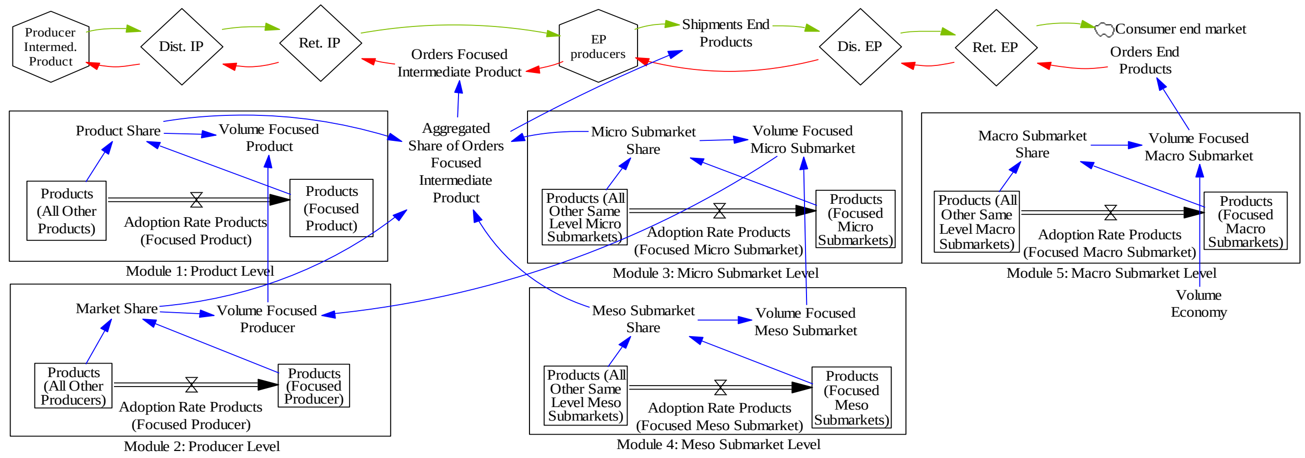

Figure 19: Conceptual model with the supply chain and the demand endogenization concept. Different modules are capturing adoption processes of several diffusion levels and are coupled to the supply chain.

Figure 19 shows the conceptual model that visualizes how demand endogenization of intermediate products will be achieved. The diagram shows a supply chain at the top with five adoption modules below. From the first echelon on the left an intermediate product is produced and shipped via a distributor and a retailer to the end product producer. This end product producer manufactures an end product which is shipped via two other distribution echelons to the consumer end market. Similar to Figure 18, a single and a multiple producer level are considered together with three different submarket levels. For each of these levels a separate diffusion module is incorporated to endogenize the corresponding adoption process. The expected amount of incoming end product orders from the consumer end market depends on the shift in the macro submarket. At the end product producers' echelon, this order volume needs to be narrowed down to the orders of the focused intermediate product. The volume of the absolute amount of orders for the end product impacts, together with the aggregated share of the focused intermediate product orders, the absolute order volume of the focused intermediate product. The aggregated relative demand of the intermediate product is at the mercy of the adoption processes in the remaining modules. The calculated shares can be multiplied with one another to compute this relative demand. It is not to be forgotten that the absolute amount of delivered intermediate products also needs to be multiplied with the reciprocal of the aggregated relative demand share to get the absolute amount of end products shipped to the consumer end market.

Conclusively, a conceptual outline is provided in Figure 20, describing how to use the envisaged framework in regard to a case study.

Step 1: Identify the product diffusion hierarchy to separate the nested adoption processes for the case under study. Make the several diffusion processes visually explicit.

Step 2: Build the modules of the different diffusion levels with the help of the theoretical model. Take into account data availability constraints. Conduct pretests of the single modules.

Step 3: Conncect the different modules among each other and to a standard SCM as shown in the conceptualisation. Latter point (conncection to the standard SCM) isn't mandatory.

Figure 20: Conceptual outline to apply the conceptual framework to a case under study.

5. The Theoretical Model

As discussed in the conceptual framework of the last chapter, the aim is to build a theoretical model which is useable as module to endogenize several adoption processes in the diffusion interface hierarchy. The model was built in a way to be general enough to incorporate (1) adoption processes of products, (2) adoption processes of products between producers and (3) adoption processes of products between different submarkets.

For the purpose to describe and explain the model, a causal loop diagram (CLD) and a stock and flow diagram (SFD) will be presented. The causal loop diagram provides a quick overview of the structure. In the CLD no deep explanations are included that provide information why structure was built in a specific way. In the SFD that follows afterwards, these explanations are included together with further details.

5.1 Causal Loop Diagram

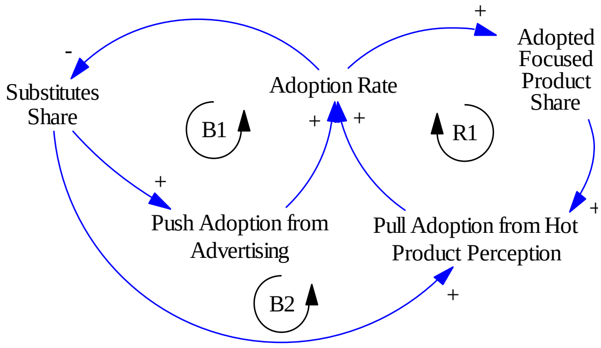

Figure 21: The Bass Diffusion model as starting point.

Starting point of the model is the BDM structure (Figure 21). This structure was already described in 3.2.2 The Bass diffusion model. In a nutshell, one variable represents the share of substitutes and another variable defines the share of the adopted focused product (AFP). The shares represent the percentual proportions. The growth of the AFP share is the decline of the substitutes share. This displacement is defined by an adoption rate, dependent of an innovative source of adoption, included in the diagram as push adoption from advertising, and an imitative source of adoption, named pull adoption from hot product perception. While the former adoption process is dependent on the left-hand sided substitutes share only, the latter variable is dependent on both mentioned shares. The diagram so far includes two balancing loops (B1 and B2) and one reinforcing loop (R1).

The first extension is to split the adoptable substitutes share into two different shares (see Figure 22), namely an unadoptable substitutes share (US share) and a potential adoptable substitutes share (PAS share). Unadoptable substitutes can become adoptable substitutes, when the attractiveness of the focused product increases. A rate, named becoming PAS rate, decreases the US share and increases the PAS share. The Becoming PAS rate is ndirectly also at the mercy of the amount of unadoptable substitutes (balancing loop B3 in the diagram)[18].

The becoming PAS rate is at the mercy of a first order balancing mechanism (tantamount to balancing loop B3). The rate is defined by using the discrepancy between an actual fraction willing to adopt (Actual FWTA) and a desired fraction willing to adopt (Desired FWTA). As also shown in Figure 22, the actual FWTA is dependent from the PAS and the US share and closes therewith the balancing loop B4 and B5. The purpose of this incorporated mechanism is explained next.

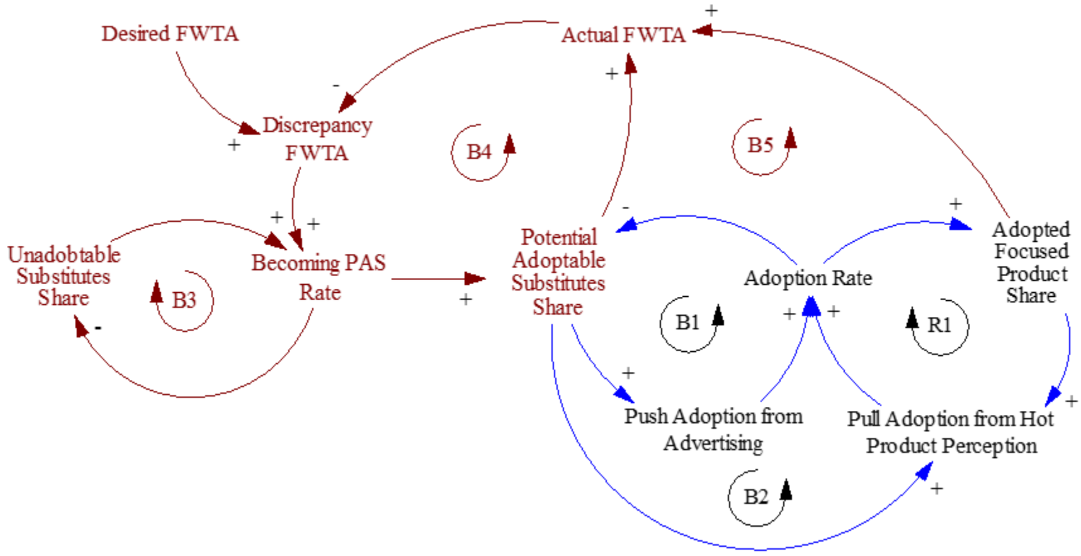

Figure 22: Distinguishing between unadoptable and potential adoptable substitutes and add of a mechanism that determines the Becoming PAS Rate.

[18] In the developed model no link from the US Share to the Becoming PAS Rate exists. But, as the rate is defined via the PAS and AFP Share in the variable Actual FWTA and in regard to the fact that the value of this variable is equal to the initial stock sum minus the US share, the indirect existing feedback here is obvious.

The Desired FWTA is dependent on a cost-benefit offsetting in regard to the performance of the focused product. For this purpose a performance variable calculates the ratio between the aggregated attractiveness and the price of the focused product (see Figure 23). While the aggregated attractiveness is determined by a multi-criteria analysis with the outcome of a static attractiveness value, the price is changed dynamically by a learning mechanism, included in the CLD as effect of learning on price. This effect increases when more experience, in terms of increased product share, is gained. The rate of diffusion measures how much new product share is added per time step. With the link from the AFP share to the rate of diffusion another loop is closed. This price learning curve is the sixth balancing loop (B6) in the model.

The relative demand of the focused product in comparison to substitutes is given with the AFP share. To be able to translate this relative demand value in an absolute demand value, the absolute demand of the focused product and substitutes together, must be known. Finally, this Demand AFP variable is also added in the figure as well as the Demand AFP & S variable.

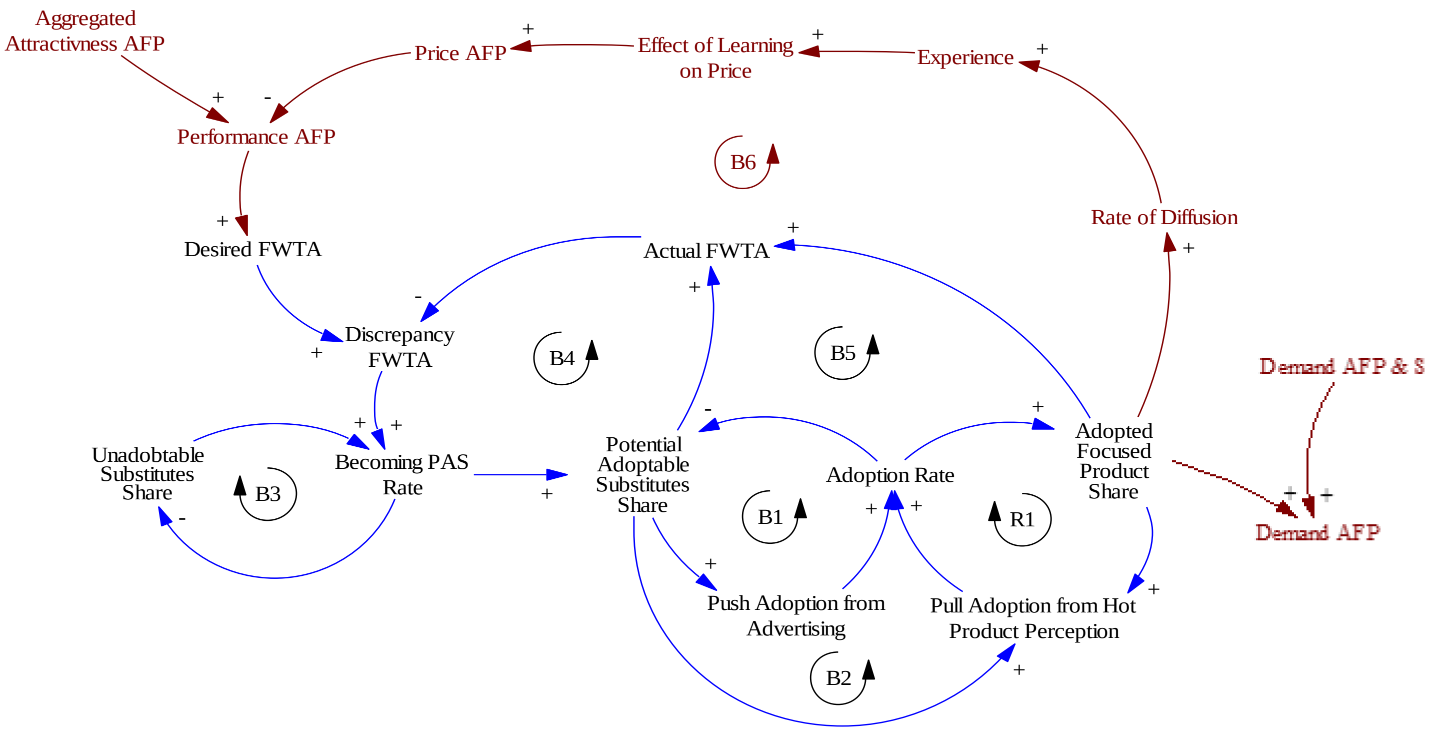

Figure 23: Including a cost-benefit offsetting, a price learning curve and calculating the absolute AFP demand.

5.2 Stock and Flow Diagram

In this section the stock and flow structure of the theoretical model that enables demand endogenization is described. For a start, the six major adjustments in regard to extending the original BDM are summarized. These are, as already briefly described in the CLD:

1. Split of the substitutes in unadoptable substitutes and potential adoptable substitutes.
2. Performance mechanism to adjust the fraction that is willing to adopt the focused product.
3. Multi-criteria analysis to calculate an aggregated attractiveness value of the AFP.
4. Cost reduction learning curve which is dependent from gained experience.
5. Rate of diffusion calculation to determine the experience increase.
6. Absolute demand calculation and connection to other modules.

In accordance with these six adjustments respectively extensions, the model is divided into six sectors plus an additional sector for stock initialization. Figure 24 shows an overview of the different sectors. The single sectors are explained stepwise next. The core sector of the model with the key elements of the BDM is located on the bottom center of the arrangement. The other sectors are arranged around this main sector. First, this core part in which the general concept of the diffusion process endogenization is located is explained.

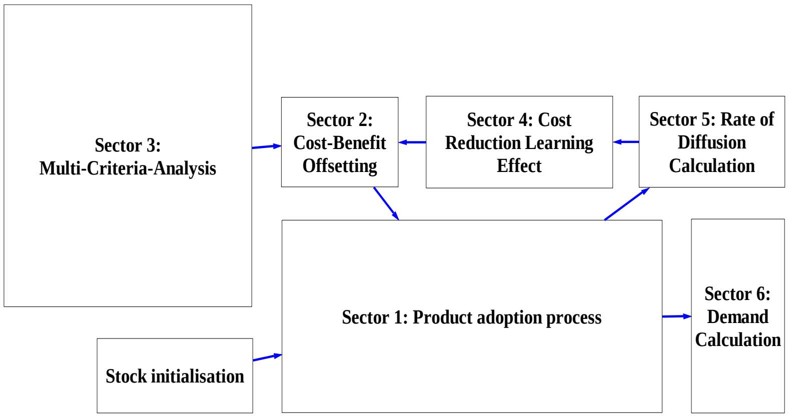

Figure 24: Sector arrangement with the primary connections between sectors.

Afterwards the other sectors will be elaborated in the reversed sequence of the feedback logic.

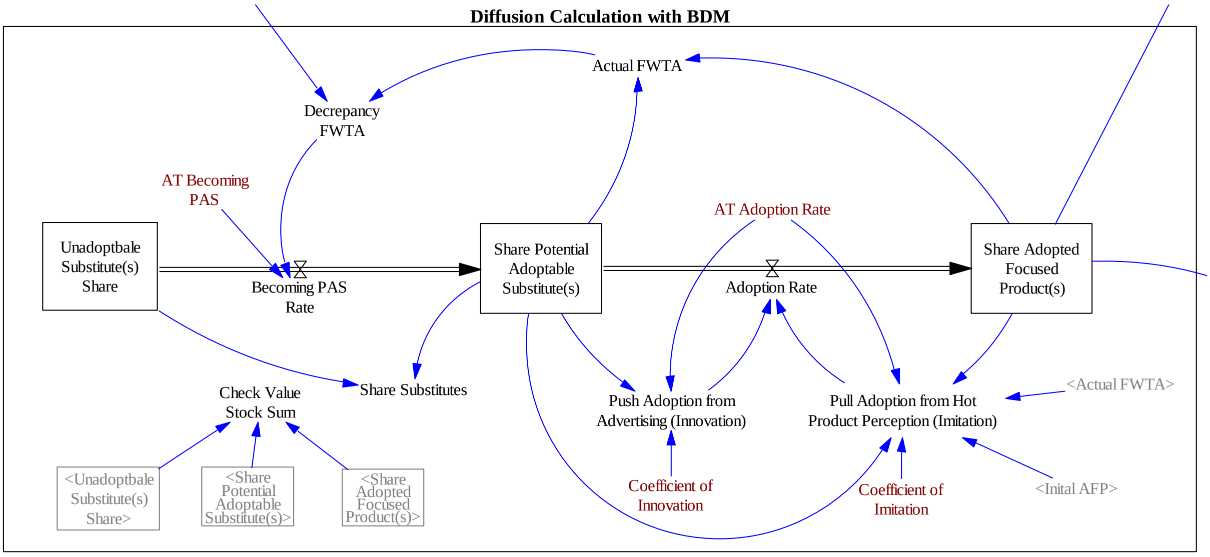

Figure 25: Sector 1 with the product adoption process.

The three stocks included in Figure 25 are representing products from one adoption level as shown in Figure 18. The stocks account the relative percentual shares and not any absolute product number[19]. As mentioned, the first major extension is the split of the substitutes into two different stocks, named **Unadoptable Substitute(s) Share** (=US Share) and **Potential Adoptable Substitute(s) Share** (=PAS Share). This split sets a boundary respectively a total limit in regard to substitutes which can be cannibalized by the focused product. The first assumption is that not all substitutes will be cannibalized, as would be the case with the original BDM structure[20]. The included split of the substitutes into two stocks leaded to a suitable solution. Adoption is only possible from the PAS stock. Adjustments between these two stocks are made by the flow **Becoming PAS Rate**. The logic can be further explained in the way that the potentially adoptable substitutes are already cannibalizable, but buyers need a stimuli to change their habit and adapt the product. Substitutes that are successfully cannibalized are accounted for the stock **Adopted Focused Products** (AFP Share). The flow **Adoption Rate** takes into account the shift from the PAS to the AFP. The adoption rate adds up the two sources of adoption, the **Push Adoption from Advertising** and the **Pull Adoption from Hot Product Perception**. Both sources are adjusted through the adjustment time **AT Adoption Rate.** In addition to that former source is dependent from the variable actual FWTA and initial AFP.

[19] Including shares simplify the structure. During pretests the calculation with shares lead to the same results, as the incorporation of absolute demand values. The advantage for using relative demand shares is that an absolute demand value could be either monetary or unit-based. The share can cover both without unit adjustments.

[20] With the original BDM, diffusion will not be stopped at some point what is indeed unrealistic for most cases. Especially for these types of cases, where the focused product is not that innovative, so that it can cut out all other products from the market.

For clarification: the mentioned stimuli can be of two different sorts, namely advertisement and the growing customer perception to get a "hot" product with buying the focused product. Therefore, the more successful advertising is, the more potential buyers respectively potentially substitutable product share is available (= push from the PAS stock). The adoption from hot product perception is also dependent from this availability. But stronger is the dependence from the amount of buyers that bought the focused product (= pull from the AFP stock). The underlying assumption is: the more products are bought, the more customers perceive the product to be good. The model has to be calibrated to adjust both adoption processes. Therefore a **Coefficient of Imitation** and a **Coefficient of Innovation** are used[21]. These parameters are static, as no feedback link changes these parameters. Looking back to the left hand side of the subsystem, the influencing mechanism of the Becoming PAS rate is explained next. The **Fraction Willing to Adopt** (FWTA) is central for the behavior of the model and determines the maximum amount of substitutable products that can be adopted at the current time step. For this purpose an explicit goal seeking balancing mechanism is implemented, consisting of the gap variable **Discrepancy FWTA**, the explicit goal variable **Desired FWTA** (located outside the sector) and the current state variable **Actual FWTA** (sum of the stocks PAS share and AFP share). The discrepancy FWTA determines together with the adjustment time, named **AT Becoming PAS**, the becoming PAS rate. At the bottom left of this sector a **Check Value Stock Sum** is incorporated to proof the consistency of the stock sum.

In the lower left corner of Figure 24 the additional sector for stock initialization is located (Figure 26). With the help of the input variables **Initial Stock Sum** and **Initial Market Share AFP** and the automatically calculated Desired FWTA the initial stock shares (**Initial US**, **Initial PAS** and **Initial AFP**) are computed. The initial stock sum is set to 100 percent, if the substitutes and the focused product cover all products in the diffusion level. The sum is initialized lower, if this is not the case.

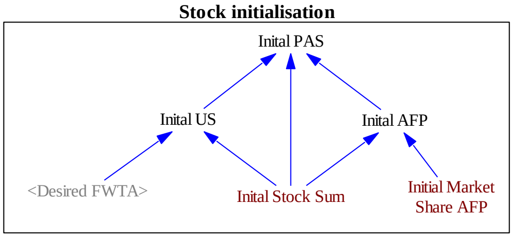

Figure 26: Additional sector for stock initialization.

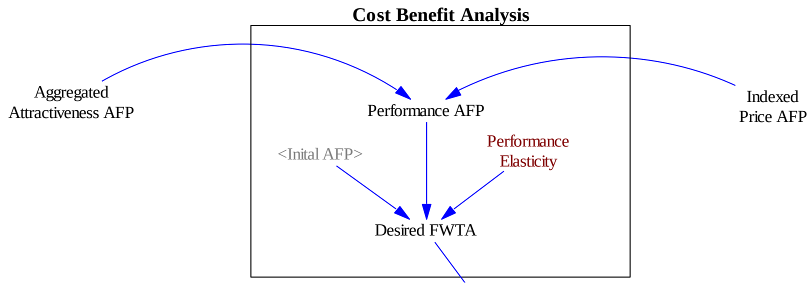

Figure 27: Sector 2 with the cost-benefit offsetting.

The sector with the cost-benefit offsetting is covered next (Figure 27). The purpose of the Desired FWTA variable that is central in this sector was already explained. The Desired FWTA is calculated via the Initial AFP share and a **Performance AFP** variable as well as a **Performance Elasticity**. The basic included assumption is: The higher the performance of the focused product, the more potential buyers are willing to adopt the product. The performance multiplier of the focused product is the ratio between the **Aggregated Attractiveness AFP** and the **Indexed Price AFP**. The attractiveness value, as an incorporated static component[22], determines the product potential and therefore also defines the initialization of the PAS stock. This attractiveness is made static, because a variation of the product will lead in a strict sense to a new product. In contrast to that the price is a dynamic component, because economy of scale effects leads to reduced production costs of the same product. The task of the performance elasticity is to adjust the performance of the focused product. The included logarithmic equation has the same function as a lookup table with the shape as displayed in Figure 28**Fehler! Verweisquelle konnte nicht gefunden werden.** would have. The advantage of using an equation is that it is more easily calibrateable.

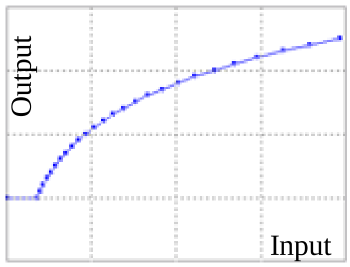

Figure 28: Shape of an exemplary performance table.

[21] As mentioned in part 3, these parameters can also be estimated through regression or another statistical method.
[22] In regard to discovered policies the value may be changed at some point in time, if the product attractiveness increases because of some exogenous changes.

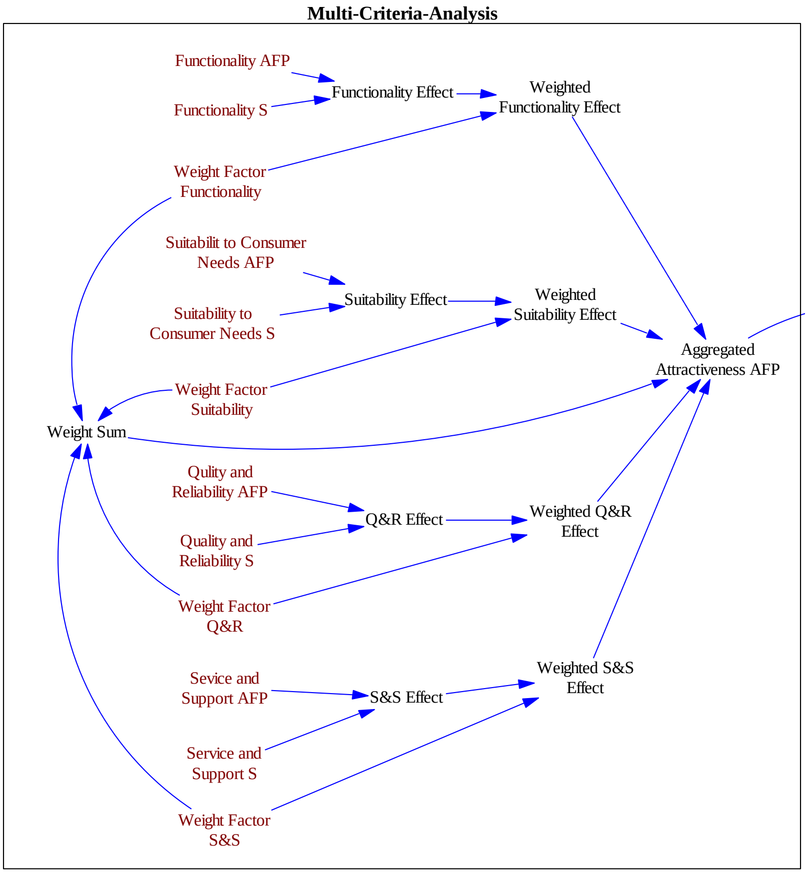

Figure 30: Sector 3 with the multi-criteria analysis in terms of attractiveness.

The left-hand-sided aggregated attractiveness of the focused product is accounted in a multi-criteria analysis. This analysis is conducted in sector 3 (see Figure 30). The incorporated attractiveness criteria to compare the focused product with substitutes is adopted from Sterman (2000): "Most products can be differentiated from those of competitors through enhanced features, functionality, design, quality, reliability, and suitability to the current and latent needs of consumers. Firms can also invest in superior service and customer support infrastructure. To the extent these investments increase the attractiveness of the products in the eyes of customers the firm can gain market share" (Sterman, 2000, p. 371f). The incorporated criteria are **Functionality**, **Suitability to Consumer Needs**, **Quality and Reliability** plus **Service and Support**. The importance of each of these factors is adjustable through **weight factors**. For a case study it is indeed possible to add more specific criteria and if a comparison of one of the mentioned criteria is not possible, the criteria can be omitted. Values for the different criteria are based on educated guesses gathered in expert interviews.

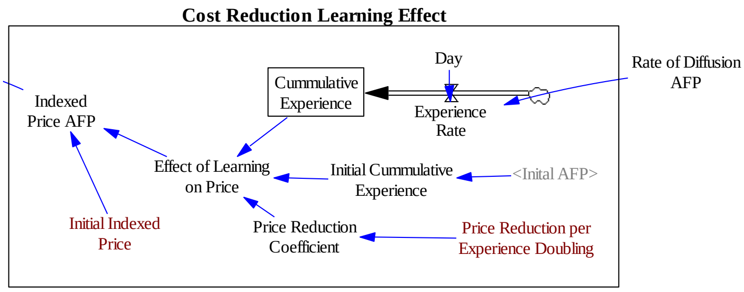

Figure 29: Sector 4 with the cost reduction learning effect.

To compare the performance of products, the price also needs to be taken into account. Sector 4 includes the learning mechanism[23] that endogenizes the price reduction of the product (Figure 29). The indexed price is adjusted through a **Price Elasticity** parameter and an **Effect of Learning on Price** multiplier. The multiplier is at the mercy from an exponential equation, including the **Cumulative Experience** over the **Initial Cumulative Experience** (= Initial AFP) as base and a **Price Reduction Coefficient** as exponent. The latter variable is set to a value by a logarithmic equation that determines how much the price is reduced when experience doubles. To make this equation more explicit, the **Price Reduction per Experience Doubling** parameter is excluded and therefore easily alterable. Sterman (2000, p. 370) points out that ten to thirty percent price reduction per doubling of experience are typical in many industries. The **Experience Rate** increases in this model, if the share of the adopted product increases (incorporated as the **Rate of Diffusion AFP**) and not as often seen in other models, absolute sales (Sterman, 2000) or investments (Arrow, 1962) increase. This is the case, because this model compares the focused product in relation to other substitutable products. The assumption is: A price reduction caused by learning effects also occurs for the substitutes. Therefore just increased adoption of the focused product can enable faster learning effects in comparison to the substitutes, because the proportional sales volume increases faster.

[23] Leaning curves are widespread in System Dynamics models. More information on learning curves is available in Sterman (2000, p. 369f).

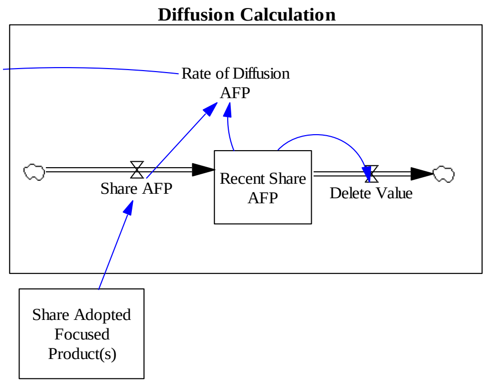

Figure 32: Sector 5 with the rate of diffusion calculation.

The rate of diffusion is the proportional increase of the share of the focused product[24]. In sector 5 the calculation of this diffusion rate is conducted (Figure 32). The rate is calculated by the division between the **Actual Share AFP** and the **Recent Share AFP**. In the structure the recent share is captured through a stock and flow storage structure including a **Delete Value** outflow to remove the last value. Mathematically this rate is the slope of the AFP share graph at the current time step.

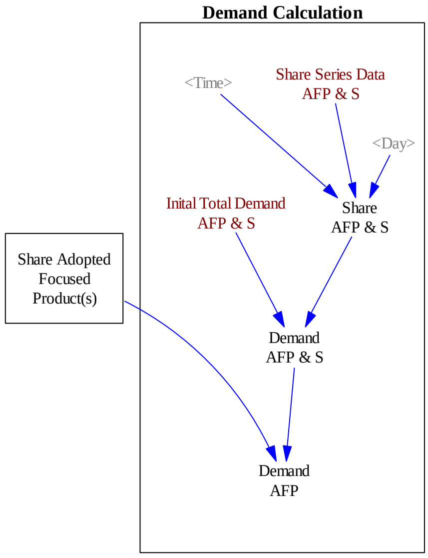

Figure 31: Sector 6 with the demand calculation.

The last sector 6, shown in Figure 31, is optional[25]. In this sector the absolute AFP demand can be calculated. Necessary are the **Initial Total Demand AFP & S** as input and the data series of the **Share AFP & S** (output from the more general diffusion process) as another input. While the first variable is given in absolute terms, the second variable is given in relative terms. The Share AFP & S takes into account the trends or alternations of the growth or decline of the AFP & S share together. The absolute **Demand AFP & S** volume can then be calculated by multiplying both inputs. And by multiplying this value with the AFP share, the **Demand AFP** is computed.

6. Summary

The goal was to develop a framework that enables incorporating endogenous demand of intermediate products traded at mid-level echelons in business-to-business environments in supply chains. To reach this goal, the theoretical grounding for incorporating demand endogenously in supply chain modeling is laid in the beginning.

For this purpose, an introduction into supply chain management was provided, by discussing the structures and the typical behavior in supply chains from the relevant literature. A distinction is made between production and distribution echelons. Structural representations of both types are presented as the basic building blocks for modeling supply chains with System Dynamics. An example of a four echelon supply chain is provided with the Beer Game. The typical empirical results of this game are shown. These curves are characterized by oscillations, amplifications and phase lags as the typical patterns in terms of the behavior of supply chains. These patterns are described to be attributable to significant time delays in the upstream information and the downstream material flows. This characteristic supply chain behavior is referred to as bullwhip effect in the literature. A generic representation of the bullwhip effect is finally provided from Forrester's original work.

After the discussion of supply chains, diffusion processes are elaborated from literature in the same chapter, because being able to model diffusion processes is indicated to be the key to incorporate demand endogenously in supply chain management. The first presented model is a simple infection model in which the infection rate behavior implied the spread of a disease. Afterwards, in regard to the developed framework, the more important Bass Diffusion model is discussed. The Bass model is described and can provide an explanation as to how the diffusion of a product is dependent on how fast the product is adopted by a potential adopter population. This Bass model is the starting point for the theoretical model that is delineated later. Furthermore,

[24] The rate of diffusion is equal to the adoption rate, if the initial stock sum is 100. But as the model should work with every explicit determined stock sum the rate of diffusion calculation is made explicit.
[25] It is optional because, if one module is used together with another module, the absolute demand of one module is not important to know. Have a look at the conceptual model (Figure 19) to recover how different modules are coupled.

specialties of intermediate product diffusion are elaborated in regard to the reviewed literature. The change from a B2C to a B2B environment is identified to be a crucial systemic alteration.

The point of departure for developing a framework to incorporate demand endogenously, was the perception that the endogenization of different diffusion processes at different diffusion levels is fundamentally important: (1) the diffusion process between the focused product and substitutes (2) the diffusion processes between product lines from different producers and (3) diffusion processes between different submarkets of which the focused product is part of. The diffusion interface hierarchy concept was developed for this purpose, illustrating which different diffusion levels are relevant for a focused product. It is necessary to aggregate the different diffusion processes of the levels which are identified to be relevant. Furthermore, the major differences in regard to intermediate product diffusion were elaborated in this part of the paper. The difference is that intermediates are traded at intermediate levels in supply chains and are bought by producers and not by end consumers. The elucidated conceptual outline to apply the developed concept to a case study includes three steps. First, the mentioned diffusion interface hierarchy need to be developed. Secondly, with the theoretical model as a kind of template, different modules are to be built for each incorporated diffusion level. And thirdly, the modules are coupled with each other and to the supply chain to provide a demand forecast.

The final aim of this paper was to develop a theoretical model that can deal with the diffusion at one diffusion level of the conceptual diffusion interface hierarchy. This theoretical model is therefore developed in a manner to be useable as a module to be applicable with other modules that take into account other diffusion levels to enable aggregation of the different diffusion processes. The theoretical model extends the Bass Diffusion model in a way to assure that not all substitutes will be cannibalized over time. Therefore, the major change was the split of the substitutes into two stocks. Adoption occurs only from one of these stocks, but between both stocks a flow takes into account that the number of substitutes that are potentially adoptable, is variable. An included performance offsetting determines the fraction of potentially adoptable substitutes. The performance calculation is dependent on an attractiveness factor which is examined through multi-criteria analysis and a price reduction learning curve that is at the mercy of the substitutes that have been adopted.

7. Discussion and Critical Reflection

The discussion and critical reflection of the paper is split into four pieces. The contribution to existing knowledge is elaborated together with managerial implications first. Afterward limitations of the conducted concept are elaborated. In the third part a critical reflection of omitted feedback processes is added. Finally recommendations for the direction of further research are provided.

7.1 Contribution to the Research Field and Managerial Implications

This paper contributes to the research field by narrowing the initially claimed gap in recent research, not to incorporate demand endogenously in supply chain management. The proclaimed aim of the paper, the development of an extension for supply chain models that puts demand forecasts in the focus, could be reached. The variable that remains exogenous in the Beer Game, the amount of incoming orders, does not need to remain completely unknown anymore, as it is possible to incorporate a forecast of this variable with the developed framework. For a few single cases demand endogenization in respect of System Dynamics and supply chain management is documented in the literature (e.g. Gonçalves, Hines, and Sterman (2005)). No work is available that provides a concept on how to endogenize demand for cases based on a conceptual guideline.

Managerial implications follow from this possibility to apply the framework to different cases under study. The developed approach can be applied to different cases in a three-step process. This process includes (1) identifying the diffusion hierarchy of the focused product (2) building of the several System Dynamics modules with the developed theoretical model to endogenize with each of them one diffusion process in the diffusion interface hierachy and (3) aggregate these diffusion processes afterwards and use the aggregate as an input for a standard SCM. In respect of usability testing and validation, the developed framework was successfully tested with a case study from the nutrition industry.

7.2 Limitations

This work was conducted as the final research project of the *European Master Programme in System Dynamics* and was limited by the time span of five months of research work. As a result of this, the scope of the research has to be narrowed down to fit the time constraints, while ensuring a sufficient depth in the area is touched upon. In the following methodological and conceptual limitations are discussed.

One methodological aspect concerns the objective of this paper. With regard to the process of endogenization, at some point, a line between endogenous structure and exogenous variables has to be drawn. Complete endogenization remains an unreachable goal. In regard to this, the methodological difficulty is to balance between simplicity that comes along with the advantage to have an easy manageable model on the one side and to take into account all possible effects and thereby increase the complexity of the model on the other side. In respect to the issue, the decision was made to keep the structure rather simple than difficult, also because of the intention to develop a generic model of diffusion processes.

The work has furthermore also conceptual limitations. The use of the same theoretical model to endogenize different diffusion processes dismisses specialties of the different incorporated levels. Applying the concept to the case study has shown that the developed theoretical model is preferably used, the more specific the focused diffusion level is. In regard to that it was not intended to use the model for fluctuating diffusion processes, where the net-flow of adoption isn’t remaining a uniflow. At the end of the paper, suggestions for possible improvement follow on this issue.

7.3 Critical Reflection about Omitted Feedback Processes

The theoretical model by itself is limited by omitted feedback processes. In the following some of these omitted feedback processes are discussed.

Omitted feedback “Share from increased advertisement”. For many situations it is probably the case that advertising of products is at the mercy of the revenue gained by these products. That means the amount of sales that these products bring, will impact the success of the adoption from advertising. In Figure 33 this omitted reinforcing feedback loop “Share from increased advertising” is presented. The AFP Share increases sales and more sales leads to more revenue and enables more advertising. And finally the higher advertising is, the higher adoption is and the more AFP share is gained. It is relatively easy to draw this loop and describe it in a qualitative manner. The expert interviews in regard to the case study have shown that it is rather difficult to quantify this feedback process. In the Bass Diffusion model this feedback is also omitted.

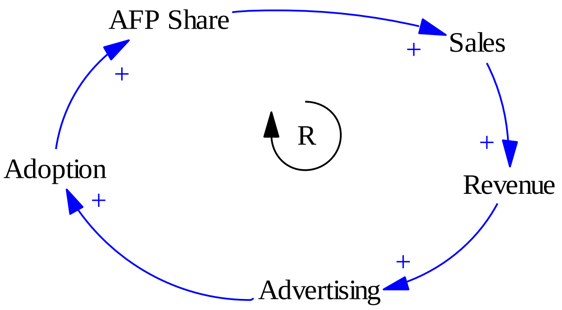

Figure 33: Omitted loop „Share from increased advertisement“.

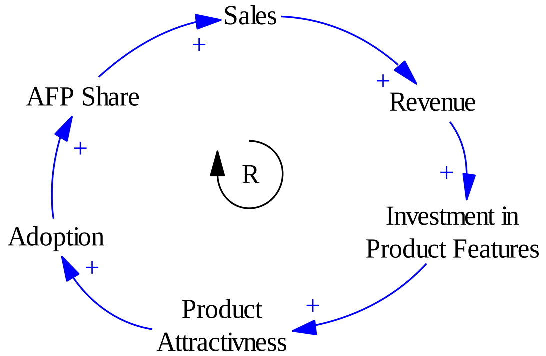

Figure 34: Omitted loop „Product feature investments“.

Omitted feedback “Product feature investments”. A positive feedback arises also from the ability of producers to invest in product features. If the success of the product grows, a firm can invest in the features of the product to increase the attractiveness of the product. Figure 34 shows this omitted feedback process. In the loop “product feature investments” more gained revenue leads to more investments in product features that impacts the attractiveness of the product and increases the adoption process. The ulterior motive to leave this part exogenous was that if the attractiveness of a product increases due to technical improvements or other reasons, strictly speaking the product is not the same anymore. The endogenization of the attractiveness would enable the incorporation of the possibility that the adoption flow switches at some point. Also this feedback isn't made explicit in the Bass Diffusion model.

Omitted feedback "Market growth from complementary goods". The attractiveness especially of intermediate products is supposed to increase by the amount of existing complementary products through network effects. In Figure 35 the omitted loop "market growth from complementary products" is illustrated. If the market size grows, the market becomes more attractive to third parties. These third parties will supply more complementary products and thereby also impact the attractiveness of the focused product to third parties. This mechanism is very easily understandable qualitatively, although it is not easy to capture this feedback in a quantitative way. This is the case for many possible feedback mechanisms which are easily understandable on a qualitative basis, but are quite difficult to take into account in respect of quantitative modeling.

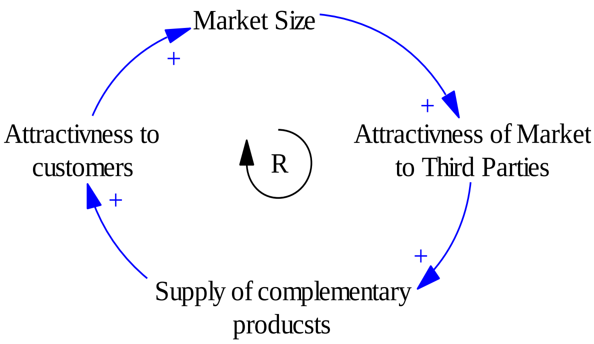

Figure 35: Omitted loop „Market growth from complementary products".

The list of omitted feedback loops could even be extended. But as mentioned, the priority was to develop a model that is well manageable, also in regard to the reutilization. Therefore not all feedback processes that could be incorporated have been incorporated. The premise was to develop a simple model first to test if the principle concept, the endogenization of different diffusion processes, works as planned. In another project the developed model can be redeveloped and for different diffusion levels different models might be developed.

7.4 Suggestions for Further Research

The model provides a structural explanation on how products diffuse into a market, resulting in nonlinear S-shaped growth dynamics. With the S-shape the model can capture the ascending phase in the life time of a product, including the introduction, the growth and the first half of the maturity phase. At some point in time, the sales volume of products starts to decline, as the product lifecycle concept (Figure 36) illustrates. The idea for improving the model is enabling to reproduce the full shape of the product lifecycle, including the introduction, growth, maturity and the decline phase. The concept to simulate a product life cycle with System Dynamics is not new, see for example Tabucanon (1981). But the developed framework would allow the endogenization of life cycles of different diffusion levels.

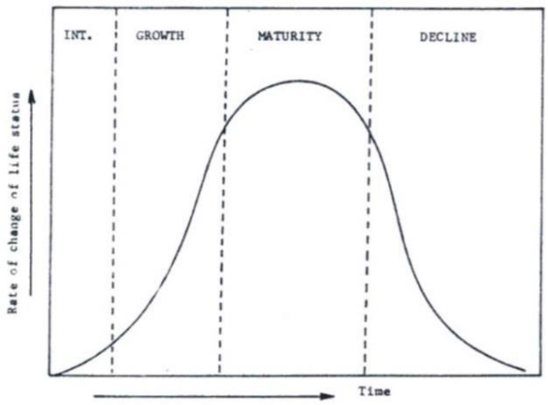

Figure 36: The product life cycle with the phases introduction, growth, maturity and decline (Source: Tabucanon (1981)).

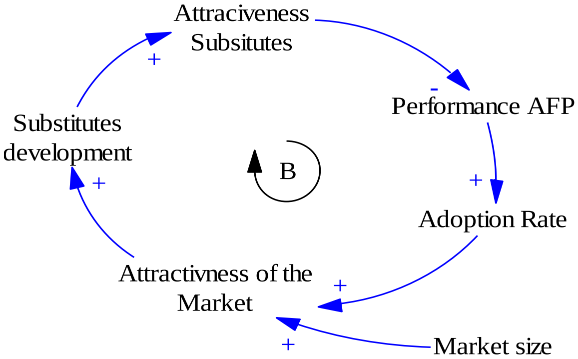

Figure 37: Omitted loop "Long term substitutes attractiveness improvements".

One responsible long term feedback effect is omitted in the model that is responsible for the decline. This omitted feedback loop is shown in Figure 37. With the growth of the market, the attractiveness of the market will rise. This risen market attractiveness will cause an increased effort to develop and improve substitutes. Therefore over time the aggregated attractiveness of the substitutes will grow and will lead to a decrease of the relative performance of the focused product. The performance of the focused product will be fallen so much at some point in time that it affects the adoption rate to become negative.

The incorporation of such a loop would enable to reproduce the whole lifecycle of the product, and not only the successful period, when the sales of the product rise. In Figure 38 the red curve shows the attractiveness of the focused product. The attractiveness is low in the beginning. Benefitting from economies of scale effects and a following price reduction, the attractiveness starts to increase. But then, at some point in time, this effect settles off, when all efficiency improvement possibilities are exhausted and so the attractiveness of the focused product reaches a total maximum. The black curve shows the attractiveness of substitutes that is impacted by the mentioned feedback loop. The aggregated attractiveness of substitutes is lower than the attractiveness of the focused product in the beginning. But better products that are brought on the market increase the aggregated attractiveness of the substitutes. At some point in time the attractiveness of the substitutes will be higher than the attractiveness of the focused product. Buyers will increasingly choose from then on the substitutes and the sales of the focused product will start to decrease as shown in Figure 36.

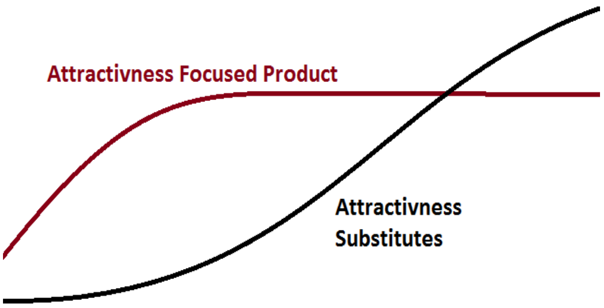

Figure 38: Technological improvement increase the attractiveness of substitutes and exceed the attractiveness of the focused product at some point in time.

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