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Early Front-End Innovation Decisions for Self-Organized Industrial Symbiosis Dynamics—A Case Study on Lignin Utilization

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Abstract: The emergence of self-organized industrial symbiosis (IS) is based on the expectations of industrial actors regarding financial and/or environmental benefits through symbiotic inter-company linkages. One such linkage is the exchange of by-products as substitutes for primary raw materials. However, the company generating the by-product may even not be aware of potential application fields in other industries. In cases where the by-product triggers an innovation, the very early phase of the innovation process ("early front-end"—EFE) is extremely important, as it is here that a first rough picture of future application fields must be defined. In contrast to traditional market innovations of industries, the EFE of IS innovations is triggered by the existence of a certain by-product. As conventional innovation models are not very helpful in supporting the EFE decisions in IS innovations, our paper aims to establish a link between self-organized IS and innovation by creating a specific theoretical framework for the support of EFE decisions. We thus introduce the "stage-gate model of self-organized IS innovations" and place a particular emphasis on the early phases within this model. Subsequently, we illustrate the application of the early phases of the model in a case study on lignin utilization in the Austrian paper and pulp industry (P&P industry). In this way, the study contributes to a better understanding of the peculiarities and conditions of EFE decisions in IS innovations and their significance in the emergence of self-organized IS networks.

Keywords: self-organized industrial symbiosis; front-end of innovation; industrial symbiosis; product/market match; lignin utilization

1. Introduction

IS leads to a shift from the traditional linear through-put model to a circular model of industrial systems, and applies the principles of industrial ecology by engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products" [1] (p. 313). There are numerous collective benefits for cooperating companies that can be achieved by establishing symbiotic linkages. Additionally, these potential benefits exceed those that can be achieved by acting alone [1]. The most important motivation for companies that are involved within an IS is the realization of economic benefits, e.g., by reducing the costs of virgin raw materials or disposal costs. Furthermore, additional revenues can be generated by new products and new markets, e.g., by the selling of the by-product. In most cases, it also leads to additional environmental benefits since the exchanged waste, by-product, or energy is used as a substitute for a primary resource and a reduction of the consumption of virgin material and energy inputs, as well as a reduction of waste and emissions, is possible [1–7]. Consequently, in addition to exchanges of energy, the focus in IS is primarily placed on the exchange of waste and by-products. The term 'by-product' is used here to refer to production output, which although largely undesirable, may in fact be recycled in one way or another. In contrast, the term "waste" refers to production outputs for which no recycling possibility currently exists (this may be due to technical and/or economic factors). Waste needs to be incinerated and/or landfilled and thus entails additional costs, as well as a negative environmental impact. Consequently, it is important for both industry and society to attempt to reduce the amount of waste by seeking recycling possibilities, i.e., to transform waste products into marketable by-products. However, as in many cases, the recycling potential within one's own firm is rather limited [8,9], and a serious attempt needs to be made to identify additional potential application fields for by-products as substitutes for raw materials in external production processes. This naturally leads to the idea of inter-company collaboration through IS, which aims at converting waste into by-products that can be used as secondary raw-materials.

According to the literature, there are several ways in which IS for by-product exchanges may emerge. These depend on the initiating actors, the prevailing motivation for the establishment of IS, and the applied procedure. Boons et al. [7] distinguish seven different types of IS dynamics (self-organization, organizational boundary change, facilitation-brokerage, facilitation-collective learning, pilot facilitation and dissemination, government planning, and eco-cluster development), where self-organization and organizational boundary change are the factors that may be initiated by industrial actors. Moreover, Chertow [3] describes two different ways in which IS in by-product exchanges may emerge in companies. The first of these is *planned IS*, where companies from different industries are clustered locally, in order to exchange resources. However, this practice is only possible if the application field for the by-products is already determined at the beginning of the investigations. For example, application fields for the by-products coal ash, sludge, and recycled paper, have been well known and successfully applied for decades (coal ash is primarily used in cement production; sludge in the production of fertilizer, clay building materials, or cement; recycled paper in the production of cardboard and other paper products or for printing; [10]). They are thus well suited for the creation of planned IS. Secondly, in the case of *self-organizing symbiosis*, the IS is not developed with the aim of establishing a network for the symbiotic exchange of by-products. Rather, it emerges autonomously through self-motivated decisions by companies that expect to gain advantages from this symbiotic exchange [3,7]. In such cases, however, the potential application fields for the by-products within the self-organized IS may not always be clear a priori. Therefore, companies have to be creative in assessing how various by-products can be re-used in an innovative way, as substitutes for primary raw material in other production processes. Even if the self-organized IS is established without a master plan for network development, it is crucial to identify and quantify the gains from this by-product exchange for all parties involved in the network. For instance, there should be a significant difference between the price of virgin material and the price of the by-product, the by-product needs to be available in a sufficient quality and quantity, and a sufficient number of potential network partners should be available [8,11]. Thus, an analysis of influencing conditions (technical, economic, geospatial, social, and institutional conditions) is also necessary at a very early stage of attention. In both the initial identification and the analysis of the influencing conditions, methodological support is provided by the "front-end of innovation" (FEI). Using FEI, an initial picture of future applications can be defined at a very early phase of the innovation process. All of the decisions made within this phase have a huge impact on subsequent innovation and product life cycle development. It is here that the quality, cost, and phasing of the entire production process are fixed, and its subsequent environmental and social impacts are determined [12–14]. At the FEI, an initial assessment has to be made considering whether the innovation is attractive for one's own company and partner companies. This entails an analysis of a by-product's technical feasibility, its market potential, and its expected environmental impact. However, classic innovation models are of little practical use in the specific case of innovations. In the present article, we thus introduce the so-called 'stage-gate model of self-organized IS innovations' and exemplify EFE innovation decisions by means of a single-case study on lignin utilization.

Although there is a rather broad consensus that innovations have an important role in the field of IS (e.g., [2,6,15–18]), there appears to be no thorough analysis of the by-product innovation process, particularly with respect to EFE activities. As stated by Chertow [3], the emergence of self-organized IS implies that there is no master plan for the network-development. Rather, IS develops autonomously via a company that is motivated to establish symbiotic collaboration for a variety of reasons. Hence, a market test needs to be carried out at the beginning of a resource exchange, in order to assess whether further exchange activities are to be pursued. According to Boons et al. [7], a company expecting benefits from IS activities is required to search for potential partners and conclude contracts with them. A detailed description of how these steps proceed is not defined.

This article aims at gaining a better understanding of the a-priori identification and assessment of potential application fields of by-products and, hence, at establishing a link between IS and innovation theory. We provide a framework including different conditions that helps to enhance the overall understanding of EFE innovation decisions in the specific field of self-organized IS. In order to achieve this, we conceptualize a theoretical framework for FEI decisions within self-organized IS, based on the existing IS and innovation literature. Subsequently, we illustrate the application of our conceptual model, with a special focus on EFE decisions, to a case study on lignin utilization within the Austrian paper and pulp industry.

The results of the study contribute to a better understanding of the peculiarities of self-organized IS networks, and of the resulting early decisions that need to be taken for the development of such a network. This ought to be particularly useful for supporting companies engaged in such decision-making processes.

2. The Front-End of the By-Product Innovation Process

The generation of innovations can be seen as a process which is triggered by various events (e.g., market pull, technology push, legal regulations, crises, information, environmental, and social requirements, [12,19–22]). The search for waste recycling possibilities represents a completely new trigger in the classic innovation process. While the classic innovation process often starts from scratch in developing innovative product ideas that fulfill customer needs, the generation of by-product innovations starts one step earlier. Based on the by-product and its characteristics, potential fields of application and substitution need to be taken into account right at the beginning of investigations. As this practice does not directly correspond to the standard approach discussed in the literature, the classic innovation process has to be reconsidered and adapted to the requirements of by-product innovations. This is described in the following section.

The innovation process entails a sequence of different phases and covers all of the activities which are necessary in moving from initial conceptualization to practical implementation. According to Koen et al. [23], the whole innovation process can be divided into three main phases, i.e., FEI, new product development (NPD), and commercialization. The FEI is the "period between when an opportunity is first considered and when an idea is judged ready for development" [22] (p. 269). FEI is the first phase of the innovation process and includes all of the pre-development activities, from the initial idea generation to the definition of future application fields. Filtering and selection in the course of assessment are used to reduce the initial possibilities to a manageable number of promising application fields, which may then enter the subsequent NPD phase.

As proceeding on the basis of instinct alone is not advisable when attempting to initiate an innovation process, one needs to gain a broad understanding of FEI activities. A literature review on the topic 'FEI' indicates that many authors addressed the early phases of the innovation process. Within the model by Khurana/Rosenthal [24], FEI starts within *pre-phase zero* by opportunity identification (through idea generation or market research activities) or by product and portfolio strategy formulation. The subsequent *phase zero* provides the product concept, which includes a preliminary identification of customer needs, market segments, competitive situations, business prospects, and an alignment with existing plans. Within *phase one*, which represents the last FEI step, the financial and technical feasibility are assessed, the product is defined, and the project is planned. Based on Cooper [19], Murphy and Kumar [25] distinguish *idea generation*, *product definition*, and *project evaluation* as important predevelopment stages of FEI. Based on the existing literature, Reid and de Brentani [26] differentiate *early front-end activities* (e.g., problem/opportunity structuring, information collection/exploration) and *late front-end activities* (e.g., idea generation, concept development, continued information collection, or prescreening). For Herstatt and Verworn [12], the FEI consists of the tasks of *idea generation* and *concept development*. Depending on the degree of newness of an innovation project, different application fields of FEI are possible. Koen et al. [23] developed the "New Concept Development (NCD) Model" and distinguished five *pre-development activities* (opportunity identification, idea genesis, idea selection, concept & technology development, opportunity analysis) that are influenced by company-internal and company-external factors. Unlike the linear concepts of FEI, the NCD is a cyclical model that considers iteration and loop-backs between the five FEI activities.

Although there is a large body of literature, no uniform description of FEI activities could be found. Furthermore, both the number and type of FEI activities differ, depending on the author consulted [23,27,28].

Due to its simplicity and versatility, the stage-gate model provided by Cooper [29] appears appropriate for the present case. Although it is a simple linear model, it remains one of the most referred to tools in innovation management. Within this model, the innovation process is systematically structured into three FEI stages (*idea, preliminary assessment, and concept*) and one NPD stage (development). Within each *stage*, activities are performed and an evaluation of the results is carried out. At various decision points (*gates*), the current status of the innovation-project is evaluated in terms of established criteria. Depending on the results of the evaluation, one then either proceeds to the next task or abandons the whole project [29]. The basic structure of the stage-gate model with different stages and gates is suitable for use in analyzing by-product innovations. However, the use of waste/by-product as a substitute for raw materials represents a relatively specific case, and thus requires some adjustment of the standard model. Figure 1 shows the resulting theoretical framework.

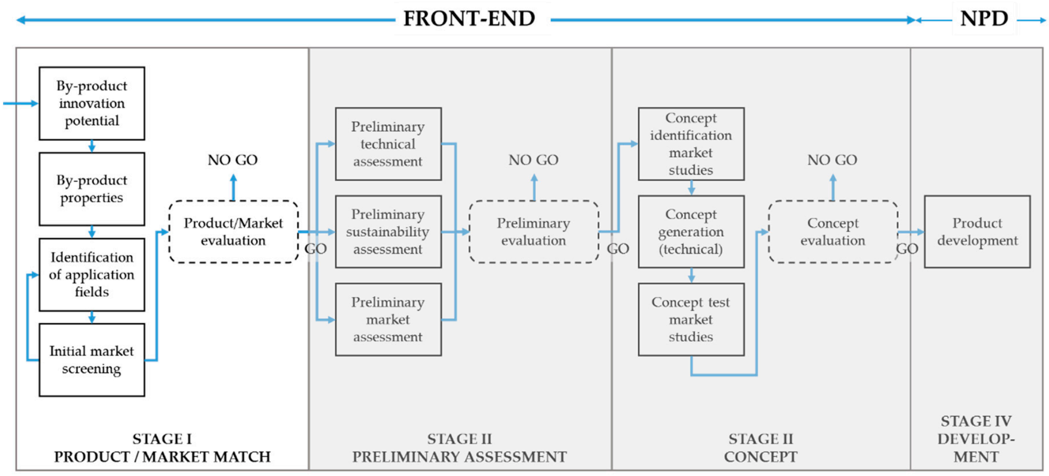

Figure 1. The stage-gate model of self-organized IS innovations (Source: the authors, based on [29]). The activities performed in the four stages (product/market match, preliminary assessment, concept, and development) of this theoretical framework are represented graphically, by rectangles. In each stage, these activities are followed by decision points (gates), which are illustrated by dashed lines.

As Chen and Ma [10] have stated, raw material may be replaced with by-products if the characteristics of the two are similar. For this reason, the technical characteristics of the by-product have to be investigated by specialists at an early stage of the whole process. Based on this, one then needs to consider which materials may be replaced with the by-product, and which potential application fields are available. This can be accomplished via a review of the literature and/or via experimentation. Market screening in the form of a *product/market match* (see Figure 1) is employed in order to narrow down the initial, relatively broad range of potential application fields. The product/market match goes beyond the first stage of Cooper's stage-gate model, in that the classical activities within the idea stage (collection of ideas and first idea screening) are replaced by a detailed analysis of the potential of by-product innovation, the by-product properties, the identification of application scenarios, and a process of market screening. The first stage is completed by the gate product/market evaluation, where an initial selection of possible innovations is made. One also needs to note that the linearity of the stage-gate model is not directly compatible with the requirements of by-product innovations, in that market screening may lead to a situation in which there is little or no market potential for the defined application fields. In such a case, it is necessary to take a step back and define new applications.

Thereafter, application fields that are selected at the end of the first stage need to be reviewed/rated within the second stage, *preliminary assessment*. In order to identify those application fields that will generate the greatest benefit for the company, its shareholders, and its employees, existing authors have tended to focus on methods used in market assessment and in technical assessment at the preliminary assessment stage (e.g., [12,23,29–32]). Market assessment allows for a comprehensive evaluation of the potential fields of application for products and services to be made. It entails an assessment of various factors, for example, the number of possible buyers, average selling prices, average annual consumption, market size, market growth rate, competition, and so on [33,34]. In contrast, technical assessment concerns itself with qualitative and quantitative parameters, with a view to reducing associated technological uncertainties. A number of studies have indicated that there is a strong positive correlation between the favorability of the preliminary technical assessment and the success rate of the project [35–38]. Both types of assessment may be used to gain a deeper insight into by-product innovations. Integrating various aspects of sustainability at the FEI is particularly important in the case of by-product innovation. For example, the reuse of waste as a substitute for raw material in production processes, instead of its disposal or incineration, needs to be considered not only from a financial perspective, but also from an environmental and social perspective. It is also not sufficient to merely consider potential material substitution in terms of expected profit margin or technical feasibility alone. In other words, one also needs to take into account the social and environmental costs associated with the achievement of such a profit margin. This thus makes it necessary to add an assessment of sustainability to market and technical assessments within the second stage of the stage-gate model (see Figure 1). However, many sustainability assessment tools are retrospective and designed for later phases in an innovation process [39]. For instance, life cycle assessment (LCA) is a frequently mentioned environmental assessment tool, but is of little use in the early stages of the innovation process due to the probable lack of accurate data for inputs and outputs [40]. Indicators or streamlined/matrix-based LCAs are more suitable for the early stages of such a process since they allow for a quick and low-cost environmental product assessment. One example is the Materials Energy Toxicity Matrix [41], which screens for the potential impacts and risks based on LCA principles. All of these results are integrated into the preliminary evaluation of the gate, during which a more specific selection is made.

The outcome of the second stage shows which innovation needs to be investigated more deeply within the final FEI stage, *development of concept*. The concept stage also contains technical and market perspectives and serves to determine a concrete business case including the concept, strategy, and design of the future product. In order to facilitate informed decision making, it consists of three steps: concept identification, concept generation, and a concept test. These finally lead to concept evaluation. Evaluation, in this context, entails deciding whether the product is worthy of realization [29]. The process of concept identification is market-oriented and focuses on the future customer. Hence, it includes all of the questions relating to the determination of the 'ideal' product for future customers and makes use of methods such as focus groups, market surveys, and key users. Competitor analysis is also undertaken. In the case of by-product innovation, it is important for customers that various aspects of sustainability be embodied in the 'ideal' product, for example, by-product innovation should result in a relative lowering of environmental harm. Various aspects of sustainability are thus taken into account in the process of concept identification. Once this is complete, the process of concept generation incorporates all of the design requirements needed in implementing the wishes of the future customer, which were collected within the previous step. These design requirements reflect technical, economic, and sustainability considerations. Following this, the concept test serves to ascertain whether the new product is at all promising and employs extended market studies in order to determine exactly what the customer expects. The concept test represents the last area of FEI activity where significant changes may still be made at relatively little cost. Once the concept stage has been completed, a decision is taken as to whether the product is to be developed, and thus, whether it may progress to the NPD stage [23,29,42,43].

As can be seen from the literature, FEI affects the subsequent innovation process, as well as, ultimately, the success of the new product. FEI and, in particular, the initial steps taken, play a crucial role within the whole innovation process, since it is at this stage that factors such as the quality, costs, process, and potential environmental influences of future application fields are all determined. In this early phase, large improvements can be achieved with relatively little effort. Improvements tend to become ever more difficult and expensive as product specificity increases [12,20,22–27,43–47]. While EFE innovation decisions are very important within the classic innovation process, they are even more important with respect to by-product innovations. In the case of a classic innovation, the process of defining application fields starts from scratch and is developed step by step. In the case of by-product innovations, starting from scratch is ruled out since it is the characteristics of the by-product and of possible fields of application which determine the FEI and subsequent innovative activities. Therefore, the product-market match represents the most important stage within our theoretical framework and will now be further analyzed in depth, based on a practical use case.

3. Methods

After conceptualization, the first stage (*product/market match*) of our stage-gate model of self-organized IS innovations was applied to a case study on lignin utilization in the P&P industry, which fitted the purpose of this paper for two reasons. First, lignin utilization is a classic example of an IS innovation. The P&P industry aims at gaining advantages from utilizing the by-product lignin as a sustainable raw material for chemicals or materials, rather than using it for energy provision on the production sites. In the sense of a self-organized IS, the formation of symbiotic intercompany-linkages for lignin utilization is based on individual decisions from P&P companies. Second, the P&P industry currently finds itself in the early front-end of the IS innovation process, for which our framework was conceptualized. Despite the various potential applications of lignin, research in many fields is still in a pilot or lab-scale stage. Thus, no clear pathways for lignin valorization currently exist and further research on the properties of lignin and on the methods to improve its quality/purity is required. Our case study was completed in a collaborative research project in Austria, with a consortium of four companies from the P&P industry and of three universities. However, the research collaboration did not aim at finding possible exploitation partners for the by-products. Rather, symbiotic exchange relations are expected to be built up on the initiative of individual pulp and paper companies, based on the research results.

In the case study, we followed the step-wise procedure proposed in the model, starting with an investigation of the *by-product innovation potential* of lignin. In this step, we drafted a sketch of the possible IS, indicating the relevant institutions within this potential network (see Section 4.1).

In step 2, we assessed the by-product properties of lignin and illustrated the current, as well as future, flows of lignin within the network (Section 4.2). Furthermore, we characterized the technical conditions of the by-product lignin and identified possible methods for lignin recovery. In addition, different quality levels of lignin were determined, and these were related to lignin reuse in different fields of application. In order to estimate the financial benefit, the economics of the by-product lignin were assessed by drawing on relevant literature and market studies. This also included the costs of recovery processes and costs of alternative energy consumption. Steps 1 and 2 entailed an iterative process of literature research and consultation with researchers and managers of the research consortium via four semi-structured interviews and two workshops.

In step 3, we identified possible *application fields* for lignin and analyzed which existing products can be replaced by the by-product, based on data from the literature and on questionnaire responses from members of the research consortium (Section 4.3). Relevant information on quantities and prices was derived by drawing on documentation relating to current lignin applications.

However, in order to assess whether the IS innovation is economically attractive, one also needs to know the range of market prices and the global production volumes of the potential lignin substitutes. Thus, in step 4, we conducted an *initial market screening* that consisted of a literature review and a market analysis based on secondary data (e.g., peer-reviewed publications, trade statistics, industry reports) (Section 4.4).

To facilitate the selection of the most promising IS innovations for the by-product lignin, we then summarized the results within a portfolio matrix (Section 4.5).

4. Results: The Case of Product/Market Match of FEI in Lignin Utilization

The following section exemplifies how the product/market match of the stage-gate model of the self-organized IS introduced above is carried out practically, based on an integrated single-case study dealing with the by-product lignin, formed during the pulp production process.

4.1. By-Product Innovation Potential

In relation to the production quantities of all of the by-products that are separated during the pulp production, lignin is the most important. It is one of the most abundant renewable raw materials available on earth since it is found in most terrestrial plants, in an approximate range of 15–40% dry weight [44]. To date, lignin has mainly been used as fuel for the recovery boilers located in pulp mills. Here, the lignin contained in the black liquor produced during the pulp process is directly applied to thermal utilization, as illustrated in the baseline scenario in Figure 2. However, instead of using lignin as fuel, which is the normal practice, it can be recovered from the black liquor (i.e., developed as a by-product inside the P&P industry) and sold for a value significantly higher than its value as a heating material. Lignin could also be used as a raw material for the production of lignin-based products (outside the P&P industry) and therefore represents the starting point for various by-product innovations that would replace one or more products already on the market (as illustrated in the by-product innovation scenario in Figure 2).

Over the last 15–20 years, there has been an increasing amount of research (private and public) on the potential utilization of lignin (e.g., [48–60]). The P&P industry is—as are other primary process industries—energy intensive and uses large quantities of water and raw material input. Large quantities of by-products, created in standard production processes, remain unused. Therefore, significant potential for the development of an IS may be assumed [61]. A wide range of opportunities for lignin utilization has been discussed in the literature. For example, Bozell et al. [50] list a total of 50 utilizations that can be categorized into three groups: near-term opportunities (source for energy production e.g., power, fuel, syngas), mid-term opportunities (macromolecules e.g., binders, carbon fibers, polymers), and long term opportunities (aromatics and miscellaneous monomers e.g., BTX, phenol, vanillin). Currently, only a small amount of lignin (1–2%—which corresponds to an amount of 1 million tonnes per year worldwide) is isolated from black liquor and used commercially in a range of low-value products and activities relating to dispersing, adhesives, and aromatic chemicals such as vanillin [48,49,51,52,55]. This rather limited field of lignin application is the result of, on the one hand, technical constraints relating to its specific structure and reactivity [56], and, on the other hand, doubts concerning its economic viability.

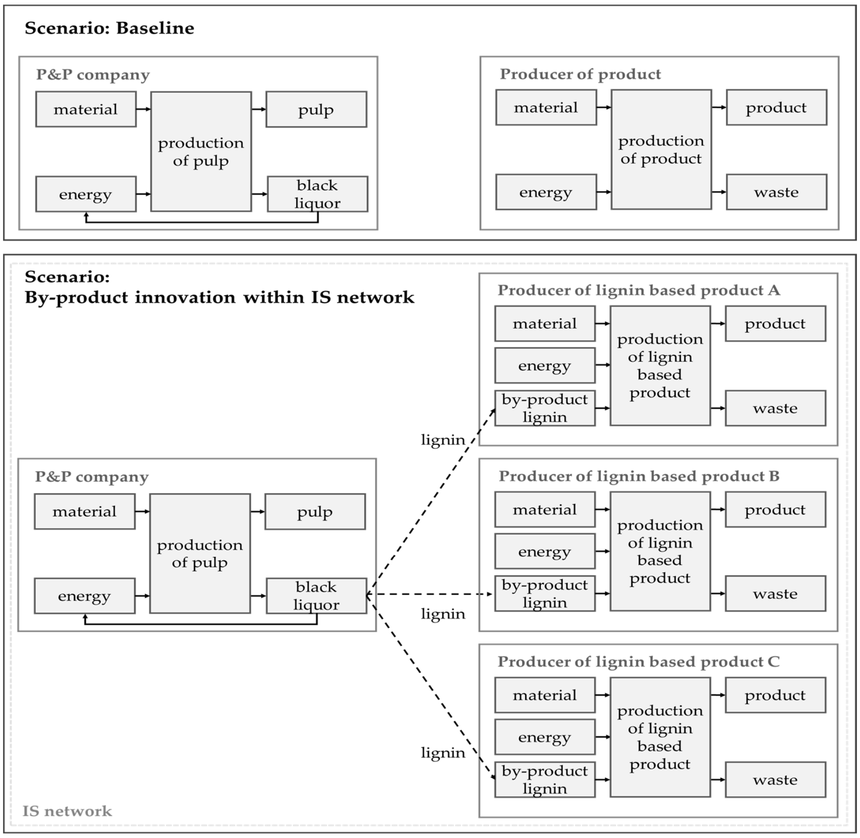

Figure 2. Baseline versus by-product innovation within an IS network for lignin utilization. The baseline scenario shows the current status quo: P&P companies using the black liquor as a fuel for the production of energy; manufacturing companies produce their products in a classic way, by the use of virgin material (for simplification just one producer is exemplified). The by-product innovation scenario is designed to outline the resulting IS network. Within manufacturing companies, the previously used virgin material is substituted (at least partially) with the by-product lignin that is isolated from black liquor. In order to assess the value of such a symbiotic formation, the entire IS network, including the lignin producing P&P company, as well as the producers of lignin-based products, needs to be taken as the unit of analysis for the case study.

Pulp and paper manufacturers (P&P companies) already have considerable experience in lignin utilization and further application is likely to demand enormous investment. It thus appears sensible to assume that producers of lignin-based products will not be found within paper and pulp, but within external industries. Any resulting IS network thus requires not only an exchange of resources and knowledge across a diverse range of companies, but also that such companies or industries are willing to work together in order to benefit from the use of lignin as a raw material substitute in their production processes [2,17,61].

In order for an IS network to be implemented, the exchange of by-products must be profitable for all companies involved. Assessing potential profitability demands that a broad analysis of the baseline and by-product innovation scenario be undertaken before embarking on the concretization of possible innovations. Lignin is mostly used as a source of energy within P&P companies. The sale of lignin can only be financially attractive for the P&P industry where it generates sufficient revenue to at least cover the cost of purchasing alternative energy supplies. The lignin sold is used as a substitute for raw materials in other companies which are probably located in different industries. These companies will only change to the production of lignin-based products if the price of the by-product is lower than the price of their existing primary raw material. An analysis of this economic condition is conducted within the second step of the product/market match according to the introduced stage-gate model of self-organized IS.

4.2. By-Product Properties

The second step within the product/market match of the stage-gate model of self-organized IS entails ascertaining the specific properties of lignin as a by-product. This involves an assessment of both technical and economic conditions, such as the costs of the lignin recovery process, the costs of alternative energy provision, and the market price of lignin.

Lignin's technical characteristics, for example its structure, purity, properties, etc., and therefore its costs, largely depend on the original feedstock, but also on the lignin recovery process. Thus, different types of lignin can be distinguished, based on their botanical origin and on the methods used for recovery [55]. Lignosulfonates, kraft, organosolv, and soda lignin are related to the various pulping processes used. As can be seen in Table 1, the various types of lignin exhibit different levels of purity. This also determines their potential for use in high value applications.

Depending on the pulping process employed, different methods have to be used in order to ensure the recovery of lignin as a valuable by-product. However, the literature on the potential costs of recovery methods is quite limited, and only relatively few scientific articles and reports deal with this issue (e.g., [52,54,58]). The costs of lignin recovery vary, according to the recovery method used. The estimated costs for the 'Lignoboost' recovery approach are €38 per tonne [54]; recovery from cooking liquor costs approximately €60 per tonne [52] and €33 per tonne from black liquor [52,58], and organosolv fractionation from nonwoody lignocellulosic biomass costs around €52 per tonne [58].

Where lignin, which is currently used as an energy source for P&P companies, is sold, alternative energy sources have to be obtained. For the sale to make sense, the costs of the new energy purchased must at least be covered by the sales revenue generated. The market price of lignin is thus instrumental in determining whether P&P companies achieve a satisfactory rate of return and/or target profit. The cost of energy is also decisive here. The potential value of a tonne of lignin may be calculated on a gigajoule basis. Gosselink et al. [55] provide a range of 15 to 22 GJ/t for the calorific value of lignin. In most cases, electricity or natural gas is used as an alternative energy source for lignin within the case region (Austria) considered here. Thus, the possible prices for energy substitution vary from €145.83 when based on natural gas, to €281.11 when compared with electricity prices (details see Appendix A Figure A1).

The market price of lignin is determined by different components, i.e., the quality of lignin, world annual production, process costs at the P&P plant, for example the costs of lignin recovery, and the costs of replacing the energy value lost due to the recovery of lignin. Table 1 illustrates the price range that can be expected for various lignin types.

Table 1. Lignin types, prices, volumes, and purity [55,59,62] [1].

Lignin Type	Price Min. (€/Tonne)	Price Max. (€/Tonne)	World Annual Production (MT)	Lignin Purity
Low-purity lignin	40	270	50,000,000	Low
Ligno sulfonates	180	400	1,000,000	Low-medium
Kraft lignin	250	550	60,000	High
Organosolv lignin	350	600	1000	High
High-grade lignin	500	750	N/A	Very high

[1] We were not able to fully confirm these figures. Our own investigation of the costs of lignin recovery and required energy purchase revealed that the minimum market price for lignin must be at least €178.83/tonne, although the price varies depending on the energy source and lignin type.

4.3. Identification of Application Fields

Different types of lignin can be used to produce specific potential products. This is illustrated in Table 2. As can be seen, organosolv and high-grade lignin are particularly suitable for the highest value products. Kraft lignin represents an intermediate material, and ligno-sulfonates and low-purity lignin can be used as a cement additive or energy source.

Table 2. Lignin types, purity, and potential application fields [55,59,62].

Lignin Type	Lignin Purity	Potential Application Fields
Low-purity lignin	Low	Energy, refinery (carbon cracker)
Ligno sulfonates	Low-medium	Adhesives, binders, cement additives and adhesives, detergents, dispersants, particle board, refinery (carbon cracker), stabilizer, surfactants
Kraft lignin	High	Activated carbon, binders, biofuel, bitumen, BTX, carbon fibers, cement additives, fertilizer and pesticide carrier, hydroxylated aromatics, phenolic resins, refinery (carbon cracker), vanillin
Organosolv lignin	High	Activated carbon, additives for paints, carbon fibers, phenol derivatives, phenolic resins, vanillin, varnishes
High-grade lignin	Very high	Carbon fibers, phenol derivatives, vanillin

Since not all potential application fields of lignin could be examined in the course of the case study, four application fields were selected for further study, i.e., adhesives, binders, fibers, and soil conditioners. It is with respect to these fields that potential product replacements are listed in Table 3. This serves as a basis for further analysis.

Table 3. Products replaced by new lignin-based products.

Application Field	Adhesive	Binders	Fibers	Soil Conditioner
Products replaced	Polyamide 6 Polycarbonate Caprolactam Phenol formaldehyde Adhesive Phenolic resin Phenol Platform chemical (bio oil)	Styrene Butadiene rubber Styrene butadiene latex Styrene butadiene rubber (except latex) Dextrines Potato starch Wheat starch Maize starch Manioc starch Starches (except P,W,Mai,Man) Starches inulin Starch residues Native starch	Carbon fiber Glass fiber (E type) Carboxymethyl cellulose (CMC)	Nitrogen fertilizer Soil Peat

4.4. Initial Market Screening

All products shown in Table 3 could, in theory, be replaced by lignin-based products. In order to determine the economic attractiveness, their market price range and the global production volume were analyzed.

Owing to its macromolecular nature, lignin offers considerable potential in *adhesive* applications, whereby its use as a substitute for phenol is frequently mentioned in the literature (e.g., [53,59,62,63]). Phenol is important for the production of plastics. It is used, for example, in the production of phenol-formaldehyde resins, polyurethane foams, or polyurethanes [59]. The price for phenolic products, based on a UN COMTRADE analysis and the work of Kraus [64], ranges from €800–€2000/tonne [65]. Other phenol-based products such as high quality epoxy resin for special applications range from €800–€15,000/tonne. In 2012, the annual production of phenol reached 8 million tonnes and is expected to grow over the next 10 years [59,62]. Thus, both the relatively high price of phenolic products in relation to the market price of lignin, as well as its overall market size, present considerable potential in the field of lignin substitution.

Lignin can also be used as a *binder*, for example in construction materials, road making. and feed pellets [63], and therefore has the potential to replace a broad range of products. The price for styrene as a binder ranges from €500–€2600/tonne for different types of starch, and from €1600–€3400/tonne for various types of styrene/butadiene latex. Levels of both starch and styrene production reach about 15 million tonnes a year [65]. Thus, once again, initial market screening reveals sufficient further potential for the use of lignin-based products in binder applications.

The next application field is the use of lignin as a substitute in various *fiber* applications, for example, glass fiber, thermal insulation, or carbon fiber. As lignin consists of about 50–60% carbon, it clearly exhibits potential for use as a carbon fiber substitute. Although the characteristics of carbon fibers means that they are suitable in numerous fields of application (e.g., civil engineering, automotive industry, aircraft and sports goods), the global production volume is not very high (27,000 tonnes/year). This is mainly due to the high price of carbon fibers, which ranges from €16,000–€24,000/tonne. The use of lignin would probably make the production process cheaper, such that lignin-based carbon fiber could be offered for a price of €6000–€10,000/tonne, with a resulting increase in global demand [59,62,63]. Prices for other applications range from €1000–€18,000/tonne for different types of glass fiber, from €2000–€2200/tonne for thermal insulation (rock wool), and from €700–€3300/tonne for carboxymethyl cellulose [65,66].

In contrast to the above, more long-term applications, such as the use of *ammonoxidized technical lignins (N-lignin)*, as slow nitrogen release fertilizers have only rarely been discussed in the literature, for example, by authors such as De la Rosa et al. [67], Neff et al. [68], or Ramirez et al. [69]. More specifically, prices per tonne for the conventional products that may be replaced by lignin as a fertilizer, range from €20–€50/tonne for peat and €450–€890/tonne for nitrogen fertilizer [65]. Owing to the low price of peat, there is currently no point in replacing it with lignin. In contrast, nitrogen fertilizers have a much higher market price and are thus more clearly suitable for replacement by lignin.

4.5. Product/Market Evaluation

In order to facilitate the selection of the most promising IS innovations for the by-product lignin, we summarized the results within a portfolio matrix approach (see Figure 3). Within this portfolio, the global market volumes of the potential areas of substitution are plotted on the horizontal axis, while the respective average world market prices are to be found on the vertical axis. For both axes, an estimation is made from low to high. Adhesives are represented by a diamond, binders by a cross, fibers by a dot, and soil conditioners by a triangle. The figure ignores those products for which no global production volume could be determined. The four quadrants of the portfolio show which IS innovations promise the greatest potential success for the by-product lignin (these are thus to be analyzed in more detail in the next stage (*preliminary assessment*) of the stage-gate model of self-organized IS innovations), as well as which IS innovations may be neglected.

Within *quadrant A*, both the attainable market price and the existing production volume of products are so low that they do not offer any promise for substitutability, and by-product exchange within a IS network will simply not be worthwhile. In the case of lignin, we can see that none of the areas of application are classified here. *Quadrant B* represents those applications characterized by a high production volume and a low market price. In this quadrant, a good competitive position is mainly determined by product price and availability. Thus, the potential for by-product substitution largely depends on the possibility of establishing cost leadership with respect to the original product. This could be achieved either by a reduction in by-product processing costs, or by an enlargement of the target group of potential substitutes by opening up new market segments or new geographic regions. *Quadrant C* represents those areas of application exhibiting high market prices, but little market volume. For such target areas, it would be necessary to expand existing business areas through product development and the exploration of alternative uses. Areas of application plotted in quadrants

B and C both offer potential. However, successful by-product exchange requires that markets or products be extended and suitable pricing/cost adjustments be achieved. Companies acting together in an IS network are more likely to be in a position to meet this challenge. *Quadrant D* represents those areas of application which offer the highest potential for by-product exchange within an IS network. These exhibit both a high market price and a high production volume.

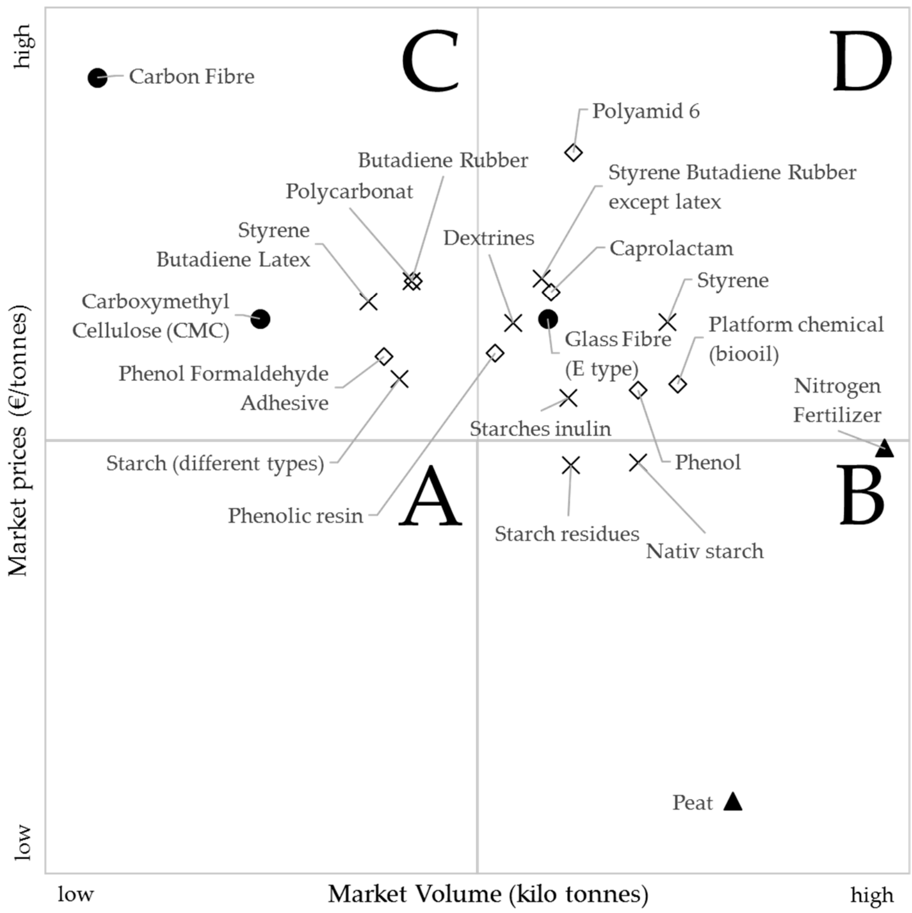

Figure 3. Plot of potential areas of application (€/tonne).

As can be seen in the application portfolio in Figure 3, the possible areas of application for lignin innovation range from commodity-type markets, exhibiting relatively high market volumes and low prices (e.g., peat or starch), to more specialized, smaller markets, in which much higher prices are possible (e.g., carbon fiber). The potential margins for lignin utilization and revenue per tonne vary from a few hundred to several thousand euros per tonne of lignin, depending on the type of lignin and the potential product. According to these results, the applications within *quadrant D* are of particular interest for further consideration. Those applications for lignin innovation should be examined in more depth within the second stage of our stage-gate model of self-organized IS innovations, i.e., in *preliminary assessment*.

5. Discussion and Conclusions

The stage-gate model of self-organized IS innovations conceptualized in this article consists of four main stages, in which different activities are performed for the a priori identification and assessment of potential application fields of by-products. Within the model, the first stage, product/market match, is especially important because decisions have to be made on the basis of relatively little information. The present paper has thus specifically focused on this stage [12,20,23,24,39]. Following a step-wise procedure, the five steps of product/market match (by-product innovation potential, by-product properties, identification of application fields, initial market screening, product/market evaluation) facilitate the quantification of the technical and economic conditions that are required to estimate the potential benefits of the by-product exchange and, consequently, of the whole IS network. This then makes it possible to select those applications for the by-product lignin which offer the greatest promise for both P&P companies and for those operating in potential areas of lignin application. The results of the product/market match stage are merely meant to serve as a rough indicator of the direction that may be taken within the self-organized IS. For example, they omit the consideration of any (structural) measures needed to adapt the production process to the new raw material. Accordingly, the results need to be refined within the further stages of the stage-gate model of self-organized IS innovations (preliminary assessment, concept stage, and development), and specific partners for the by-product exchange within the IS network need to be selected.

The theoretical framework developed here was applied to the case of lignin utilization in the P&P industry. This is just one example of a self-organized IS. As this framework is applied to a specific single case study, it may not be concluded that the framework is generally applicable to other cases where innovation is triggered by a by-product. Thus, with regards to the case of lignin utilization, future research will focus on the assessment of potential applications using methods associated with the second stage of FEI. We also suggest that further research be undertaken in order to evaluate the potential of the use of multicriteria decision-making methods in fostering the process of integrating economic and technical information into the FEI.

Within the developed theoretical framework, technical and economic conditions are considered in more detail. Alongside this, geospatial conditions, as well as social and institutional conditions, are also relevant for a self-organized IS. Geospatial conditions describe the local proximity between symbiotic industrial facilities. It is only when companies are clustered locally or regionally that the establishment of an IS network makes sense. Otherwise, additional costs and the environmental burdens incurred, e.g., by transportation, would offset or exceed the potential benefits. For many authors, the geographical proximity of network partners is a prerequisite for IS [1,2,4,7,15]. The verification of the geospatial conditions could be integrated into the first step, product/market match, where the potential benefits of the by-product innovation is determined. As already mentioned, a rough sketch of the potential network is created within this step and could therefore be supplemented by the geospatial perspective, analyzing the distance between industrial actors, as well as the infrastructure. Long distances and/or a lack of accessibility and infrastructure hinder exchange. In a self-organized IS, social and institutional conditions are important, e.g., in the form of collaborations [1,17], and are not limited to the exchange of by-products. Rather, knowledge transfer or network coordination is also required to leverage already existing applications for by-products or to find new ones [2,61,70]. This is possible, for example, through joint R&D, where experts from different companies participate, often with the support of research facilities or universities [3].

Like other process industries in the primary sector, the P&P industry is very energy intensive, consumes large quantities of virgin material, and produces by-products that are not completely utilized. There is thus a high potential for more diverse IS, especially in the field of by-product utilization [60]. The stage-gate model of self-organized IS innovations introduced here, may serve to support companies creating innovations through by-product exchanges and enable them to gain benefits from symbiotic exchange with other companies.

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Appendix A

Energy Source	Type	avg. heat value [GJ/tonne]	avg. price [€/MWh]	avg. price [€/GJ]	Possible price for lignin/ton (on equivalent GJ basis) low (€)	high (€)	Source
Electricity	Electricity industrial		46.00	12.78	191.67	281.11	E-Controll 2015
Gas	Natural Gas industrial		35.00	9.72	145.83	213.89	Statstik Austria 2014
Lignin	Lignin low energy content	15.00					Gosselink et al. 2011
	Lignin high energy content	22.00					Gosselink et al. 2011

* Natural Gas is specified in MJ/m³
** Natural Gas is specified in €/m³

Figure A1. Calculation of possible price for lignin/tonne (on equivalent GJ basis).

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