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Utilization of product lifecycle data from PLM systems in platforms for Industrial Symbiosis

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Abstract

Industrial Symbiosis represents a promising approach to foster the transformation towards a circular economy. To involve businesses in Industrial Symbiosis, online platforms and input-output matching tools for facilitating the exchange of by-products have been provided by industry organizations and facilitators. Regarding the discrete parts and product manufacturing industry (DPPM), little success is being reported for such platforms and tools. Within the scope of this research, a list of Input-Output matching tools was analysed regarding data sources which are currently used for input-output Matching. Specifications of by-products in the DPPM industry were reviewed in order to identify a list of requirements for data sources. Shortcomings of the currently existing input-output matching tools were identified and suggestions for additional data sources used for input-output matching in IS in DPPM were given. Results show that datasets currently used do not include organisational data sources such as Product Data Management (PDM) systems, Enterprise Resource Planning (ERP) systems, Supply Chain Management (SCM) systems, and or Manufacturing Execution Systems (MES).

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Keywords: Industrial Symbiosis, Industrial Ecology, Product Lifecycle Management (PLM)

1. Introduction

The limited capacity of the atmosphere to store emissions of our carbon-based economies poses a threat not only to natural equilibria but also to conditions of living [1]. The agreement signed at the 21st Conference of the Parties

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(COP 21) of the United Nations Framework Convention on Climate Change [2] in December 2015 has put additional pressure on the efforts concerning climate change [3]. Limiting the global warming to less than 2°C compared to pre-industrial levels will require industrial sectors to decarbonize their emissions drastically until 2050. Energy and resource efficiency of processes need to be enhanced dramatically in order to reduce corresponding process-related emissions [4]. As a major stakeholder in many areas of human living, the industrial sector plays an important role in addressing this challenge. In particular, the Discrete Part and Product Manufacturing (DPPM) sector does not only have a direct impact on the environmental load through production emissions but also influence resource consumption of products over their entire lifecycles, thereby playing a critical and complex role in sustainability [5].

Despite resources becoming ever scarcer, human society and industry are producing vast amounts of waste. Together, the member countries of the Organization for Economic Co-operation and Development (OECD) are the largest waste generators on the planet, producing around 1.75 million tonnes per day. This volume is expected to increase until 2050, owing to urban population growth [6]. Industrial waste makes up half of the total amount of waste that the world generates annually. Forty per cent of all industrial waste ends up in landfills every year. By-products of industrial activity account for 50% of all the industrial waste produced annually across the globe [7].

The manufacturing industry can and has to address these challenges by improving resource efficiency through the integration of approaches that ensure that natural resources are saved, by-products are reused, waste is prevented, harmful substances are not used, and the wellbeing of humans in the value creation process is secured [8]. Modelling industrial activity according to the principles of biological ecosystems where material systems are closed is gaining increasing attention in academia, as well as among political and economic thought leaders. According to a recent report of the European Parliament, the net savings from closed material systems within Europe are estimated to be €600 billion in material savings, 2–4% reduction of GHG emissions, and the creation of two million jobs [3].

2. Theoretical background and State of the Art

2.1. Concepts of a Circular Economy

The concept of a *Circular Economy*, which is restorative and regenerative in design, has attracted much attention in recent years [9]. *Circular Economy* encompasses different material recovery techniques such as reuse, remanufacturing, and recycling [9], as well as frameworks for closed material systems, such as the *Blue Economy* [10], *Industrial Ecology* (IE) [11], and *Industrial Symbiosis* (IS) [12]. The waste framework directive of the European Commission specifies the hierarchy of waste from the least favourite option to the most favourite option (landfilling, energy recovery, recycling, reuse/remanufacturing, minimization, and prevention) [13]. Since the term 'waste' implies no or little value, the term 'by-product' for originally unintended derivatives of manufacturing, created besides the desired product through industrial processes, is used within this paper.

Frosh and Gallopoulos coined the term Industrial Ecology (IE) to depict the design of manufacturing entities in analogy with natural ecosystems [14]. As a sub-discipline of IE, Industrial Symbiosis (IS) aims at optimizing resources among collocated companies [15]. IS engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products [16]. In an ideal Industrial Symbiosis, by-products and energy are shared among different organizations, which ultimately reduces the consumption of virgin material and energy inputs. The generation of waste and emissions is therefore reduced [17]. The geographic co-location of production plants with possible synergies in terms of waste streams facilitates the exchange of the physical flows that are involved [5]. Herrmann et al. describe the symbiotic integration of factories into their surroundings as one aspect of factories of the future [18]. Cerdas et al. propose the concept of a Circulation Factory, where manufacturing, remanufacturing and recycling is combined into an integrated system [19].

Although IS has developed into a notable research topic, it has not been adopted by a large number of industrial organisations [12]. Efforts by public and private institutions have been made to improve the systematic planning and development of IS over the past decades [20]. Practitioners consider it crucial to find ways to get buy-in from businesses, which is essential for success. Many practitioners noted the significance the importance of using the language of business (costs, revenues, risk, etc.) to generate this buy-in [21].

2.2. IS in the discrete parts and products manufacturing (DPPM) industry

DPPM is characterized by a flow of output of individual products, each distinct from the other. It can be contrasted with process manufacturing, where the product is created by using a formula or recipe to refine raw ingredients and the final product cannot be broken down to its basic components [22]. The by-product streams in DPPM vary in many aspects compared to those of the process industry. Most DPPM processes are convergent manufacturing processes, whereby parts are manufactured into sub-assemblies that are combined to form the finished product. Continuous manufacturing processes are divergent manufacturing processes. Here, common raw materials enter the production process and, by the end of the production process, this input is divided into many different products with differing colours and sizes. Some examples are aluminium products produced in a rolling mill with varying widths and thickness, and paper products of different sizes, colour and coatings [23]. Since by-products in DPPM have usually passed through various transformation processes and possess a certain shape, they usually need to be recycled before they can be utilized in another value creation process. Reutilizing the by-product directly will save the value that has been added to it.

Nevertheless, large amounts of geometrically defined by-products are occurring in the DPPM industry, such as metal and wood cut-outs and cut-offs resulting from cutting, sawing and pressing processes. Furthermore, obsolete semi-finished parts and products are falling through quality gates and become obsolete. While reusing and repurposing by-products from DPPM in further industries is less common, numerous analogue examples can be found in the apparel industry. For instance, Puma is partnering with Saitex, a Vietnamese denim manufacturer, for its Re-Cut shoes which are made from Saitex's post-industrial scraps. The resulting products require only minimal or no conversion processes to the utilized by-products and waste-materials (i.e. manufactured fabrics), taking advantage of the value added to those in preceding processes (e.g. weaving process) [24].

2.3. Input-Output Matching for Industrial Symbiosis

The concept of input-output matching for IS aims at allocating the by-product outputs of one process to the raw material inputs of another process [20]. In order to support this process, material flows and process chains have to be tracked and documented, and data and information exchanged [25,26]. In spite of various attempts to create web-based matching platforms, most of these tools have ceased to be used, having made little impact on the development of IS linkages [27]. Consequently, there has been no report of a standardized and internationally accepted methodology for defining and classifying IS and regional resource synergies [28].

A crucial aspect for the matching process is the collection and classification of data [29]. Actors involved in the planning and development of IS rely on manual interpretation of information [30]. A further challenge regarding IT support for IS lies in the identification, extraction, and provision of relevant data to sufficiently describe a by-product and allowing it to be evaluated for its usefulness in other industries. Owing to the complexity of modern products, data regarding their lifecycle are usually dispersed among multiple members of value creation networks with heterogeneous IT system landscapes. As products undergo different stages of processing in the value creation network, their properties are modified in various ways. In each of these processing stages, product-related data are generated and stored in the respective companies' organizational and technical environments [25].

3. Research Gap

Concluding from the aforementioned state of the art, there is a clear need for an extended research on input-output matching tools and platforms for Industrial Symbiosis.

Two central challenges regarding IS can be summarized:

1. **The concept of IS has not been transferred to the DPPM industry so far**.

The principle of IS has mainly been tested in process industry and is not recognized in DPPM. Reasons for this have not been specified in academic literature. Yet, transferring the concept to the discrete manufacturing industry and overcoming the respective barriers could unlock large opportunities for waste and emissions reduction as well as resource consumption reduction.

2. **The IT platforms and input–output matching tools that have been developed for IS require high efforts for manual data processing and hence have fallen from use.**

This paper intends to address these challenges by presenting an analysis of the utilized data sources in input-output matching tools and –platforms and comparing them to the occurring by-products in the DPPM industry. The central research questions followed were:

A. *Which data sources do current ICT tools and platforms use for the identification of by-product symbioses?*
B. *Which types of data are required for matching by-products in the DPPM industry?*
C. *Which data sources could be integrated in existing Input-Output Matching tools and platforms in order to facilitate IS in the DPPM industry?*

4. Methodology

In order to address the research questions a descriptive study has been conducted in four steps. For step 1, a list of input-output matching tools was created in order to receive an overview of previous research activities. In a second step, literature was analysed in order to identify the data sources which are currently used for input-output matching. In a third step, the specifications of by-products in the DPPM industry were reviewed in order to identify a list of requirements for data sources. Finally, shortcomings of the currently existing input-output matching tools were identified by comparing the results from step 2 and 3 and suggestions for additional data sources used for input-output matching in IS in DPPM were given.

For the each of the first two steps a Systematic Literature Review (SLR) has been conducted. SLR is providing guidance for conducting a *systematic*, *explicit*, *comprehensive* and *reproducible* literature review, allowing for 'identifying evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars and practitioners' [31,32] and grasping complete compendium of literature on a mature and narrow scientific domain.

The comprehensive corpus of published research gathered thanks to this method has been screened in order to identify implementations of the researched concepts. The results are presented in the following section. The SLR reported here is based on the method defined by Okoli and Schabram (2010) as an adaptation of a method for systematic reviews in medical sciences to the field of information technology, which is applicable to engineering science in general. The SLR as defined by these authors contains eight steps: (1) the purpose of the literature review, (2) protocol and training, (3) searching for literature, (4) practical screen, (5) quality appraisal, (6) data extraction, (7) synthesis of the studies and (8) writing the review [32]. The implementation of the steps 'purpose of the SLR', 'searching for literature', 'practical screen', 'data extraction' and 'synthesis of the studies' is reported in the next subsection. In a second step, the utilized data sources for the identified tools have been analysed. For this purpose, available literature regarding the tools was reviewed and data sources collected. Finally, the results were compared with available data sources from industry and suggestions derived on how tools and platforms may be improved.

5. Results

5.1. Input-Output Matching Tools & Platforms

Regarding the support of input–output matching, there is a growing trend of using of internet-based IT tools such as Synergie by International Synergies, or the Resource-eXchange-Platform as part of the ZeroWIN EU project to further promote coordination and exchanges. Developed tools have been delivered by Grant et al and can be found in Table 1 [27].

Online platforms for facilitating exchange of by-products have been provided by industry organizations such as the United States Business Council for Sustainable Development (USBCSD), or facilitators such as National Industrial Symbiosis Programme (NISP). These platforms aim for allowing businesses a safe and common platform for discussing synergies through symbiosis [33].

Table 1:Tools for input output matching for Industrial Symbiosis

Tool	Authors	Reference
Knowledge-Based Decision Support System	Boyle and Baetz 1998	[34]
Dynamic Industrial Materials Exchange Tool	Shropshire et al. 2000	[35]
Match Maker!	Nobel and Allen 2000	[36]
WasteX	Clayton et al. 2002	[37]
Industrial Ecosystem Development Project	Kincaid and Overcash 200	[38]
Residual Utilization Expert System	Fonseca et al. 2005	[39]
Institute of Eco-Industrial Analysis Waste Manager	Sterr and Ott 2004	[40]
Industrie et Synergies Inter-sectorielles	Massard and Erkmann 2007	[41]
SymbioGIS	Massard and Erkmann 2009	[42]
Core Resource for Industrial Symbiosis Practicioners	Laybourn and Morrissey 2009	[43]
Industrial Ecology Planning Tool	Nobel and Allen 2000	[36]

5.2. Data Sources currently used in Input Output Matching Tools for IS

The data sources currently used in input-output matching tools for IS could be classified in four categories: proprietary databases, custom-made databases, structured sources and unstructured sources. Proprietary databases are used to monitor industrial activities such as industrial sectors and volumes, or planning and marketing datasets. Further examples include project management tools, such as environmental records or quality management practices [30]. Custom-made databases offer access to case studies, which can be reviewed for information [27]. Structured sources encompass e.g. company registration, waste exchange registry databases, the national pollutant emissions inventory, geographical information systems (e.g. Google Maps) and lifecycle inventory databases. Financial reports, information from company websites, online news, social media, online encyclopaedias and journal corpus can be understood as unstructured data [44].

Processing this data in order to achieve matches is challenging. The information has to be interpreted first in the context of specific knowledge domains. Then, the resulting implications have to be evaluated when combined with further data on the surrounding value creation network (e.g. materials, technologies and objectives, environmental effects, economic and social benefits). With increasing complexity of the network (e.g. inclusion of new technologies, inclusion of additional stages for by-product pre-processing, pre-treatment, transportation, and storage), it becomes quite apparent that a thorough analysis of data is impossible through manual manipulation of data [45,46]. Furthermore, Grant et al. criticize the available datasets as outdated and unable to assist innovation [27].

5.3. Required data for Input-Output Matching in IS for DPPM

A critique of current ICT systems supporting is related to their tendency to focus on explicit knowledge, whereas tacit knowledge is essential for the mutual, nonmarket interactions required for IS [45]. Furthermore, a standardized data model for by-products represents a crucial challenge to ICT support for IS. Without a data model for the comparison of available resources, the developed systems lack a common language in order to produce relevant search results [27].

Specific differences between the process industry and the DPPM industry lie in the type of products produced by each industry and the related by-product streams. Products and by-products can be either discrete or non-discrete. Discrete by-products are characterized by non-continuous flows, a solid state of aggregation, and a defined geometrical form (e.g. metal cut-outs). Non-discrete by-products are usually characterized by continuous flows and a liquid or gaseous state of aggregation (e.g. water, steam, fly ash, sludge, bioethanol, etc.). As the further utilization potential of such by-products largely depends on elemental characteristics (e.g. chemical composition, degree of purity), they can be sufficiently described by textual information.

While by-products in the process manufacturing industry are predominantly non-discrete, DPPM is characterized by an output flow of individual by-products, each distinct from the other. During the manufacturing of a product from raw material to a semi-finished product and then to a finished product, they usually pass through multiple processes of transformation. In each of these processes, the value of the by-product is enhanced, since its characteristics are modified in order to fulfil a specific purpose and function. The utilization of such individual by-products as raw material in other production processes usually requires another conversion process that would diminish the added value. Reutilizing the by-product in its individually shaped state can maintain its higher value, prevent additional transformation processes, and unlock significant resource- and energy-efficiency potential.

Unlike commodities such as recycled metals, which can be traded solely based on explicit knowledge, by-products are typically nonstandard, off spec, or highly variable in composition. Exchange of discrete by-product streams, compared to traditional commodity exchanges, requires the communication and application of knowledge about the by-product itself and a broad understanding of how it can be utilized in further processes [27]. Understanding how knowledge is communicated requires a distinction between two types of knowledge: (1) explicit knowledge or information and (2) tacit knowledge or expertise. Explicit knowledge or information is easily communicated, codified, or centralized using methods such as statistics. Tacit knowledge, on the other hand, is usually more complex and cannot be codified easily. It is revealed through application and context, and is therefore costly to communicate between people and organizations [47]. Furthermore, tacit knowledge or expertise can neither be transferred vertically through a hierarchy nor to and from a central authority [48]. For instance, cardboard and paperboard may be substitutable or identical inputs for a by-product process, but their equivalence is based on a more tacit knowledge that is not easily coded into a computer system. Similarly, resources like 'waste water' require a long list of attributes for a computer to establish an acceptable match [27]. Therefore, computer-aided input–output matching requires high upfront investment to create standardized classifications for resources and associated computer interfaces that allow users of widely varying backgrounds and languages to input and retrieve relevant and recognizable information [41].

5.4. Synthesized suggestions

Within each company, data regarding different aspects of the product's lifecycle may be further managed by different IT systems such as Product Data Management (PDM) systems, Enterprise Resource Planning (ERP) systems, Supply Chain Management (SCM) systems, and or Manufacturing Execution Systems (MES) [26]. Hence, there is a high complexity in terms of information management, especially if information has to be exchanged across company borders. In such cases, data from multiple IT systems have to be retrieved and pre-processed according to the partner's requirements (e.g. data format) and organizational rules (e.g. intellectual property protection). Consequently, data exchange with adjacent members of the value creation network is often limited to the bare essentials, while the greater parts of product-related data remain 'hidden' in the company's IT systems [49]. With regard to IS, some data regarding by-products may not even exist (e.g. CAD models) as they are not relevant to the manufacturing of the actual product. Data about metal cut-offs, for example, may be recorded in quantitative matters (e.g. Kilograms per coil), but not in qualitative matters (e.g. geometrical shape). In other cases, data may be recorded, but not available in the required form. For the evaluation of the re-usability of a by-product, data regarding used lubricants from previous processing stages might be relevant (e.g. for compliance with environmental regulations). Such data are most likely recorded as part of the manufacturing process of the respective suppliers; however, they are not available to other members of the value creation network. We therefore suggest the usage of organisational data systems such as PDM, PLM, SCM, ERP and MES.

6. Conclusion

The previously developed tools for input-output matching have been reviewed within the scope of this research. In recent approaches, novel concepts such as ontology engineering are introduced in matching tools and platforms for IS, since they can help to express tacit knowledge, which is essential for the mutual, nonmarket interactions required for IS. Data sources which are currently used for input-output matching have been identified. They include proprietary databases, built to monitor activities of industry, custom-made databases that offer access to case studies as well as structured and unstructured sources. The evaluation and analysis of these data sources regarding IS is challenging. Specifications of by-products in the DPPM industry were reviewed in order to identify requirements for data sources. In comparison with by-products from the process industry, by-products occurring in DPPM are characterized by non-continuous flows, a solid state of aggregation and a defined geometrical form. In order to fulfill their specific function and purpose, they have usually passed through multiple value creation processes. To sufficiently describe such geometrical formed by-products, additional information on geometric properties and physical appearance has to be added. Within each company, data regarding different aspects of the product's lifecycle may be further managed by different IT systems such as *Product Data Management* (PDM) systems, Enterprise Resource Planning (ERP) systems, Supply Chain Management (SCM) systems, and Manufacturing Execution Systems (MES). Utilizing these data for input-output matching tools and platforms can add functionality to existing approaches.

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