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Industrial symbiosis implementation by leveraging on process efficiency methodologies

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Abstract

Resource efficiency is a crucial step for manufacturing companies to improve their operations performance and to reduce waste generation. However, there is no guarantee of a zero waste scenario and companies need to look for new strategies to complement their resource efficiency vision. Therefore, it is important to enroll in an industrial symbiosis strategy as a means to maximize industrial value capturing through the exchange of resources (waste, energy, water and by-products) between different processes and companies. Within this, it is crucial to quantify and characterize the waste, e.g. to have clear understanding of the potential industrial symbiosis hot spots among the processes. For such characterization, it is proposed to use an innovative process efficiency assessment approach. This empowers a clear understanding and quantification of efficiency that identifies industrial symbiosis hot spots (donors) in low efficiency process steps, and enables a plausible definition of potential cold spots (receivers), in order to promote the symbiotic exchanges.

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1. Introduction

Researchers and practitioners agree on the high degree of contextualization that affects industrial symbiosis solutions [1] [2]. The peculiarities and main characteristics of the production processes involved are suggested among the key features impacting on the contextualization of an industrial symbiosis solution [2] [3] [4]. Thus, an analysis at process level of manufacturing plants could potentially be a primary source for the identification of industrial symbiosis opportunities adapted to the context in which the manufacturing company operates. This research focuses on understanding how process efficiency methodologies could enable the identification of industrial symbiosis opportunities at manufacturing process level.

This article presents a proposal based on a novel process efficiency methodology, the Multi-layer Stream Mapping

(MSM), to address contextualization challenges at manufacturing process level for industrial symbiosis solutions identification.

The strength and novelty of this proposal resides in the fact that it combines characteristics of different types of tools to support industrial symbiosis implementation. The different typologies have proven to have certain limitations, which their effective combination could allow to overcome, creating a new comprehensive and flexible tool for different business contexts.

This article is structured as follows: Section 2 highlights the background on types of tools used to support industrial symbiosis applications and introduces the MSM methodology; Section 3 describes the proposed approach to integrate industrial symbiosis aspects into MSM; Section 4 discusses main findings and suggest further steps for this research.

2. Background

2.1. Review of tools used for industrial symbiosis

Reviews on tools and approaches proven useful in industrial symbiosis projects have been performed by several authors from different perspectives, e.g. based on their applications in industrial parks [5] [6] or focusing on Information and Communication Technologies (ICT) supported tools [1].

Chertow [5] categorised the tools used in 12 industrial symbiosis projects into three types: *Input-Output Matching tools*, *Stakeholder Processes tools* and *Materials Budgeting tools*. *Input-Output Matching tools* aim at matching inputs and outputs of various companies to suggest possible exchanges; *Stakeholder Processes tools* aim at considering a multi-stakeholder perspective through community involvement techniques to reach agreement and consensus, such as design charrettes used to define guiding principles for the design of Eco-Industrial Parks (EIPs); *Materials Budgeting tools* aim at mapping material and energy flows in a system, indicating reservoirs, fluxes, sources and sinks of materials and energy.

Grant et al. [1] reviewed 17 ICT tools built explicitly for industrial symbiosis purposes. Most of the tools targeted opportunities identification processes. These tools focused on 3 approaches: *New Process Discovery*, *Input-Output Matching* and *Case Study Mimicking*. *New Process Discovery* tools aim at identifying a transformation that will convert a waste into a usable resource. *Case Study Mimicking* tools aim at identifying already successful exchanges through the use of standardised codes that could support the understanding of replicability possibilities.

All these approaches for tools and methods to enable symbiosis have pros and cons and the preferred use of one of them would strongly depend on the user of the tool and the context of application. They can be used as stand-alone tools or combined with each other or with other tools. Stakeholder Processes and New Process Discovery tools are those most likely to be used as complement of the other typologies.

Input-Output Matching tools are often used to link co-located companies in industrial parks [1] [3] [7] or in a particular region [8] [9]. This approach seems to be useful, though a potential risk of overemphasizing on “what if” scenarios has been suggested [5]. Besides, it represents a challenge for ICT supported tools as they would require a common language for materials, energy, water and by-products across multiple industries [1] [10].

Materials Budgeting tools are used to map materials, energy and water flowing through a specific system [5]. They are based on the calculation of mass and energy balances to achieve a higher control of resources entering and exiting the production systems over specific time periods. This enables to uncover existing exchanges and easily identify potentials for industrial symbiosis [5] [11]. Material Flow Analysis (MFA) is one of the most common tools in this category; it is usually applied to industrial parks to identify all existing flows between different companies, as well as flows currently

leaving the system with a certain amount of unexploited value [11] [12] [13].

Case Study Mimicking tools enable companies to imitate successful symbiotic relationships implemented by similar companies (companies from the same industrial sector or with similar production processes) or including similar waste materials [14]. These types of tools provide ideas on what kind of exchanges could be worth to implement and how, making available an important amount of knowledge developed in previous cases [1] [3] [10] [14].

The main gaps identified in relation to the available tools for industrial symbiosis solutions are summarized in Table 1.

Table 1 Summary of main challenges by tool typology

Typology	Main implementation gaps /challenges
Input-Output Matching	Provide support to start conversation with potential partners, however, effectiveness is compromised due to semantic issues and lack of information on production processes
Stakeholder Processes	Adequate for consensus on overall aspects / principles, however, how to be used at implementation stage is unclear / unknown.
Materials Budgeting	Provide knowledge on different flows within the system, however, they do not support to identify symbiosis opportunities.
New Process Discovery	Adequate only if complementing other tools, such as Input-Output Matching.
Case Study Mimicking	Adequate to trigger ideas, however, cannot be used to identify available/required materials in specific context nor to visualize the efficiency of the production process

The presented typologies of tools have therefore complementary pros and cons. The work presented in this paper investigates how their benefits can be brought together building on a specific process efficiency tool.

2.2. Multi-layer Stream Mapping (MSM)

The Multi-layer Stream Mapping (MSM) is a resource efficiency assessment methodology designed according to the Lean principles of value and waste. It is based on the Value Stream Mapping (VSM), a well-known Lean tool aimed at identifying and quantifying “value added” (VA) and “non-value added” (NVA) activities at each stage of the production system [15] [16]. The MSM expands this traditional concept of VA and NVA considering dimensions other than time, which is the one traditionally included in the VSM [17]. Its main goal is in fact to allow companies to assess the overall performance of their processes, and therefore to identify all kinds of losses (i.e. time, energy, water, raw material, etc.) associated to each process unit, with a particular focus on energy and resource efficiency [17]. It is designed to foster continuous improvement, building on four main pillars [18] [19]:

- 1) The assessment of all VA and NVA activities: in analogy with the VSM, the user is guided to map losses and misuses along the production process, from the customers’ needs to raw materials (upstream). This includes the

identification of all material, water and energy inputs and outputs.

2) The systematic definition of Key Performance Indicators (KPIs) in the form of efficiency ratios: variables influencing the efficiency of the production process and the value added to the product through each process unit are individuated, and related KPIs in the form of simple ratios are created. KPIs vary between [0-100%] where 100% represents the best obtainable value.

3) The application of Visual Management techniques: four colors (red, orange, yellow, green) are associated to four intervals of KPIs' value in order to enable an easy evaluation of their trends (see Fig. 1).

4) The aggregated representation of efficiency per process unit or per dimension. In the first case, efficiency ratios related to time, energy, materials, etc. are aggregated for each process unit, while in the second case efficiency ratios related to different process units of a single production process are aggregated considering one single dimension. In this way, it is possible to have integrated efficiency indicators, thus allowing to have the efficiency of the whole process under control as well as to easily identify the major losses. A dashboard summarizes the main values to keep the process under control.

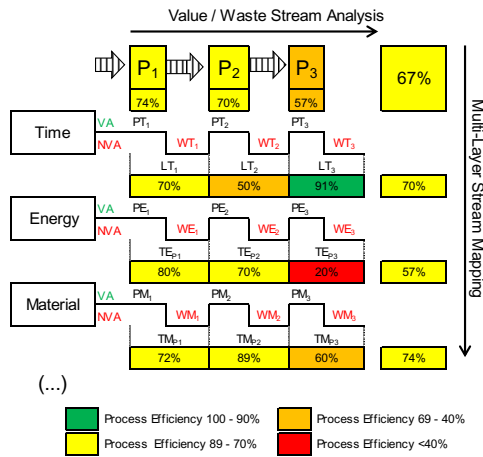


Fig. 1. Conceptual example of a MSM dashboard (adapted from [20]).

This methodology uses a systematic non-dimensionalization of the KPIs that characterize the production system, with the ratio between the portion “that adds value” to the product and the “total of the variable that enters the unit process” (see equation 1). Such particularity enables consecutive aggregation of the efficiency ratios along production system, sectors, or even plants, adopting a bottom-up analysis.

$$\Phi = \frac{\text{Value added Fraction}}{\text{Value added fraction} + \text{Non-value added fraction}}$$

The MSM is not only to be considered as an assessment tool, but also as a valuable support for decision making. It can

in fact be used to identify most critical variables and process parameters regarding efficiency, as well as potential efficiency improvement opportunities, and to evaluate efficiency improvement of implemented improvement actions over time [20]. In addition, companies can use the MSM also to create “what if” scenarios and therefore to simulate and evaluate the impact of certain improvement actions on different performance dimensions of the production process.

Moreover, the results obtained from the resource efficiency assessment identifies and quantifies the inefficiencies and misuses - the ones accounted as non-value added. Therefore, this approach is also be used to scrutinize: “where” - along the production process; “what” - variables and process parameters; and “how much” - VA and NVA values, can a process unit and/or a production system, or variable improve its efficiency, and consequently cost and environmental performance[17]. Such capability is of great importance for decision-making, since in some cases the process unit, or even the whole production system in a factory, have good operational results, but the efficiency is not as high as it could be.

The costs related to each resource, process unit and process parameters can also result from the MSM approach. The results enable a simple cost analysis which address the VA and NVA costs, namely for resource variables. Such results may support in the identification (“where” and “what”) and quantification (“how much”) of the inefficiencies and misuses costs. Such results, may assist in the definition of priorities regarding the implementation of improvement actions or in identification of critical variables, and may enable to focus on reducing misuses and non-value adding actions [19].

3. Proposed approach

The MSM is based on a VSM perspective complemented with the analysis of input and output resources. Thus, integrating a resource efficiency perspective together with a process efficiency perspective. This work investigates the prospect to enhance these perspectives with an industrial symbiosis approach. It foresees the integration between MSM - a process and resource efficiency assessment methodology - and an industrial symbiosis implementation strategy, which aims at maximizing industrial value through the exchange of resources (waste, energy, water and by-products) between different processes and companies. Two main steps of an overall implementation strategy for industrial symbiosis are initially used to illustrate our proposed approach: the identification of industrial symbiosis opportunities within production processes and the definition of an industrial symbiosis solution, including valorization of the potentially exchangeable resource and its exploitation plan.

The novel approach, depicted in Fig. 2 aims at supporting informed decision-making processes and implementation of strategies for continuous improvement regarding sustainability and resource efficiency performance. The main connections between efficiency results and industrial symbiosis are related to the identification and quantification of process waste. Thus, it could simultaneously identify potential donors - “hot-spots” and receivers - “cold-spots”,

using MSM, that will support the identification of industrial symbiosis opportunities. Ultimately, MSM could support the definition of exchange maps and routes between hot and cold spots in order to underpin industrial symbiosis potential, through the development of solutions bringing benefits to both donors and receivers processes. This would consequently increase the overall efficiency of the system and reduce inefficiencies and misuse costs.

This integration will be enabled by a set of rules to define hot-spots and cold-spots, which will be created according to a set of industrial symbiosis principles. Further rules will be defined for the identification of exchange maps and routes. The underlying concepts behind these rules are explained next.

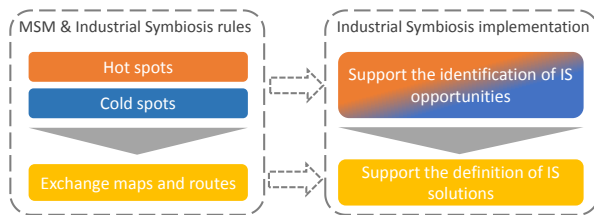


Fig. 2. Integration approach of MSM and industrial symbiosis applications

3.1. Hot-spot definition in the context of industrial symbiosis

A hot-spot is defined as a process unit that is a potential donor of an exchangeable resource (e.g. material, water, energy or by-product) to another process unit. From an industrial symbiosis perspective, waste and secondary outputs generated as well as resources that are ineffectively used or underutilized are adequate candidates to be transferred to another production process for their reuse. This is aligned with the “How to see waste” primary approach defined by Holgado et al. [21].

Within the MSM methodology this can be captured by identifying a process unit with a NVA related to a resource that features a stable quantity and quality. For such quantification MSM, as mentioned, is used to identify and quantify the NVA amount of resource in each process unit.

Besides the quantity and quality, a potential hot-spot, could be a process unit with a NVA related to a resource that is very expensive or classified as a scarce or critical, e.g. rare materials. As mentioned, MSM considers the costs related to each resource, so it can support the identification of costly materials. Regarding the identification of critical materials, such verification could be done while identifying all material and energy inputs for the production process, i.e. inventory. This is a necessary step of MSM for the resource efficiency assessment.

Nonetheless, it needs to be kept in mind that a steady quantity and quality of NVA resources may not be directly related to a definite hot-spot. This possibility needs to be compared with the implementation of process improvement

actions, e.g. possible change in process technology or enhancement of process efficiency. Process improvement actions may have an impact on the quantity and quality of the NVA resource generated in the production process. Therefore, before highlighting a hot-spot in a process unit, an analysis of possible improvements in efficiency (i.e. reduction of the NVA) should be performed to have a better understanding of the NVA resource availability expected from the system.

3.2. Cold-spot definition in the context of industrial symbiosis

A cold-spot is then defined as a process unit that is a potential receiver of an exchangeable resource from a hot-spot. Target cold-spots, from an industrial symbiosis perspective, are good candidates to include an alternative input resource into the process. An enabling characteristic to become a cold-spot is the lack of tight specifications for the input resource, as this will bring flexibility in terms of quality specifications of the infeed resource. Therefore, very tight specifications reduce the potential to accommodate alternative resources, i.e. the process is less likely to become a receiver for those resources.

Moreover, a cold-spot can be characterized by the consumption of expensive, scarce and /or critical resources, regardless of the current process efficiency. These resources are good candidates to look for substitutes without their current constraints. The MSM cost analysis may also allow to monitor price changes. In this regard, cold-spots could also be identified as process units in which an infeed resource price varies with stock-market price or subject to low supply chain reliability or availability. The rationale behind this is the possibility to reduce resource price volatility by using infeed from a hot-spot rather than depending on market or supply chain changes.

3.3. Exchange Maps and Exchange Routes

The creation of exchange maps and routes will illustrate the possibilities to match hot-spots and cold-spots between two different production processes. This will build on a set of rules, under development, complementary to the current MSM approach to process and resource efficiency. Two types of rules will be defined: (1) rules to identify hot-spots and cold-spots in each production process; (2) rules to match hotspots and cold-spots between production processes.

Due to the complexity in defining donors and receivers, related to the high degree of contextualization needed for each case, the identification of process units as hot-spots and / or cold-spots follows a logic of degrees of likelihood. Therefore, the layout mapping will feature a color code to show the degree to which a process unit could potentially be a hot-spot and a cold-spot. The color code proposed is shown in Fig. 3. The colored squares will appear next to the process unit, one to show the degree to which it is likely to be a hot-spot and a second one to show the degree to which it is likely to be a cold-spot. This is illustrated in Fig. 4.

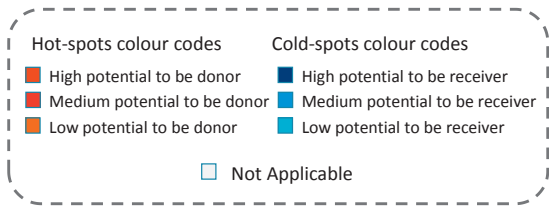


Fig. 3. Colour codes to illustrate potential to be donors / receivers

The definition of the degree to be a potential donor / receiver will be based on a selected set of criteria (related to the concepts explained in sections 3.1 and 3.2) and evaluated with a semi-qualitative approach. A numerical figure will be assigned to three pre-defined ranges of the selected criteria. This will be informed by practice-oriented information from previous known application of industrial symbiosis and by expert’s knowledge. The quantification will be done independently for the potential to be donors and to be receivers.

The second type of rules will enable to visualize the possible matching of hot-spots and cold-spots. This will bring up the routes to connect different production processes through the exchangeable resources. The information for these rules will provide from different sources such as expert information and knowledge repositories. Example of one knowledge repository is the “Library of Industrial Symbiosis case studies” and the linked “Exchanges Database” described in Benedetti et al. [14]. This will support the definition of the most common matches for different types of exchangeable resources from already successful symbiosis applications or feasibility studies. This approach allows to identify the routes and also to compare them, in case a hot-spot could provide a resource to more than one cold-spots or vice versa.

The results of this analysis for alternative routes comparison will be very case specific and can be also supported by MSM. A conceptual example of how the

exchange maps and routes could be implemented is given in Fig. 4.

4. Discussion and next steps

Making industrial symbiosis solutions implementation more practical is a main aspect of concern in order to promote its wider dissemination in industry.

This work takes as starting point a tool inspired by the very well-known and well proven VSM approach. The VSM approach is widely implemented within waste management purposes but has not been related to uncovering industrial symbiosis opportunities in the literature. Several tools, derived from VSM, are used for waste flows visualization using colour codes [22] [23] [24]. The features of MSM, as a multi-layer efficiency assessment methodology, makes it especially suitable for its extension to contribute to the identification of industrial symbiosis opportunities and support the decision-making processes related to solutions definitions and implementations.

The MSM provides also a means to assess the feasibility of different routes in terms of value and costs related to the production processes. It also allows practitioners to evaluate the possibility of taking an industrial symbiosis approach for a particular process unit against the possibility of performing process improvement actions for the same process. This is consistent with the need not to rush into an industrial symbiosis application, but instead ensuring that it is the optimal mechanism to solve the specific resource efficiency problems in a certain production process [4] [25] [26].

Taking a process oriented approach does not restrict industrial symbiosis applications to inter-firm exchanges. It also enables to identify possible exchanges both intra-firm, i.e. within the same company but different production processes, and inter-firm, i.e. between different companies. One limitation of this approach is that MSM needs to be initially implemented in all the processes and companies willing to be involved in the evaluation of potential resource exchanges.

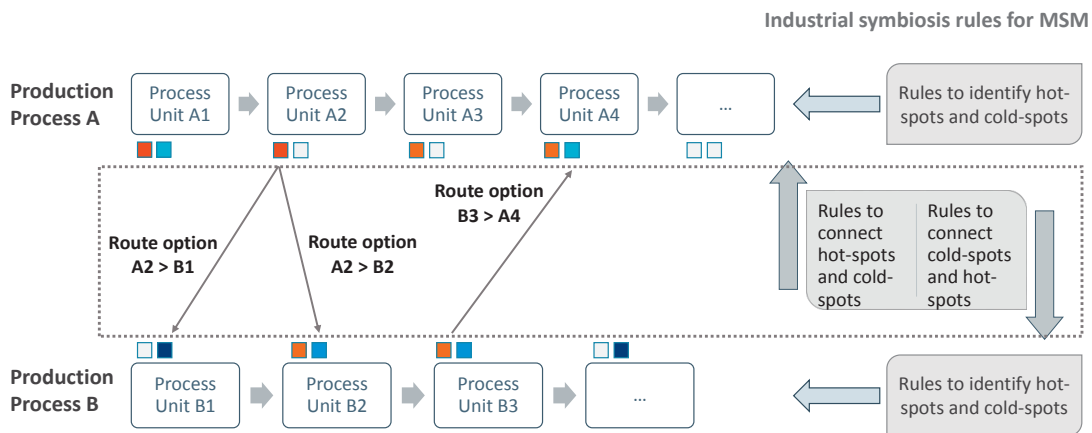


Fig. 4. Conceptual example of rules application to the identification of hot-spots, cold-spots and possible exchange routes for two production processes

The next steps regarding this work will focus on advancing the definition of the industrial symbiosis rules to be integrated in MSM and testing the proposed approach in an industrial case within an ongoing research project. A fundamental area to advance this research regards the identification of the key criteria to identify donors / receivers, their relevant ranges and their weights to be used in the semi-qualitative assessment of the potential of process units to be donors and / or receivers.

An action research approach will be taken to ensure a comprehensive testing of the methodology. A collaboration has been established with a manufacturing company to enable this testing. Researchers will be directly involved in the selection and analysis of data and in the subsequent interpretation of the results. The testing process will encompass two phases. A first intra-company testing in a multi-factory setting will be done to test a first set of rules and the data needed for implementing the rules. Then, a second testing is envisaged in a case with several companies, e.g. an industrial park, to further test and improve the rules and the data sharing mechanisms to enable the application and validation of our approach among different companies.

The testing will lead to refinement iterations of the rules and methodology in order to an easy to use step by step method to be widely used for manufacturing companies from different industries.

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References

- [1] Grant, G.B., Seager, T.P., Massard, G., Nies, L.: Information and communication technology for industrial symbiosis. *Journal of Industrial Ecology*. 14(5), 740-753 (2010)
- [2] Boons, F., Chertow, M., Park, J., Spekkink, W., Shi, H.: Industrial Symbiosis Dynamics and the Problem of Equivalence. *Journal of Industrial Ecology*. DOI: 10.1111/jiec.12468 (2016)
- [3] Cecelja, F., Raafat, T., Trokanas, N., Innes, S., Smith, M., Yang, A., Zorgios, Y., Korkofygas, A., Kokossis, A.: e-Symbiosis: technology-enabled support for Industrial Symbiosis targeting Small and Medium Enterprises and innovation. *Journal of Cleaner Production*. 98, 336-352 (2015)
- [4] Holgado, M., Morgan, D., Evans, S.: Exploring the scope of industrial symbiosis: implications for practitioners. In: Setchi, R., Howlett, R., Liu, Y., Theobald, P. (eds) *Sustainable Design and Manufacturing 2016*. Smart Innovation, Systems and Technologies 52. Springer, Cham (2016)
- [5] Chertow, M.R.: Industrial symbiosis: literature and taxonomy. *Annual Review of Energy and the Environment*. 25(1), 313-337 (2000)
- [6] Kastner, C.A., Lau, R., Kraft, M.: Quantitative tools for cultivating symbiosis in industrial parks: a literature review. *Applied Energy*. 155, 599-612 (2015)
- [7] Raafat, T., Trokanas, N., Cecelja, F., Bimi, X.: An ontological approach towards enabling processing technologies participation in industrial symbiosis. *Computers and Chemical Engineering*. 59, 33-46 (2013)
- [8] Aid, G., Brandt, N., Lysenkova, M., Smedberg, N.: Looplocal – a heuristic visualization tool to support the strategic facilitation of industrial symbiosis. *Journal of Cleaner Production*. 98, 328-335 (2015)
- [9] Jensen, P.D., Basson, L., Hellowell, E.E., Leach, M.: "Habitat" Suitability Index Mapping for Industrial Symbiosis Planning. *Journal of Industrial Ecology*. 16(1), 38-50 (2012)
- [10] Trokanas, N., Cecelja, F., Raafat, T.: Semantic approach for pre-assessment of environmental indicators in Industrial Symbiosis. *Journal of Cleaner Production*. 96, 349-361 (2015)
- [11] Sendra, C., Gabarrell, X., Vincent, T.: Material flow analysis adapted to an industrial area. *Journal of Cleaner Production*. 15, 1706-1715 (2007)
- [12] Bain, A., Shenoy, M., Ashton, W., Chertow, M.: Industrial symbiosis and waste recovery in an Indian industrial area. *Resources, Conservation and Recycling*. 54, 1278-1287 (2010)
- [13] Wu, J., Pu, G., Ma, Q., Qi, H., Wang, R.: Quantitative environmental risk assessment for the iron and steel industrial symbiosis network. *Journal of Cleaner Production*. 157, 106-117 (2017)
- [14] Benedetti, M., Holgado, M., Evans, S.: A novel knowledge repository to support Industrial Symbiosis. In: *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing 2017*, Springer (ed). 443-451 (2017)
- [15] Shook J., Rother M. *Learning to See: Value Stream Mapping to Add Value and Eliminate MUDA*. 1999.
- [16] Haefner B., Kraemer A., Stauss T., Lanza G. *Quality Value Stream Mapping*. *Procedia CIRP*. 2014;17:254-9.
- [17] Lourenço E. J., Baptista A. J., Pereira J. P., Dias-Ferreira C. Lourenço, E.J., Baptista, A.J., Pereira, J.P. and Dias-Ferreira, C.: Multi-layer stream mapping as a combined approach for industrial processes eco-efficiency assessment. In *Re-engineering Manufacturing for Sustainability*, 427-433. Springer, Singapore. (2013)
- [18] Baptista, A., Lourenço, E., Silva, E., Plebanek, S., Pawlik, E., Gil, M.: D2.1 Efficiency Framework concept description. Available at: <https://maestri-spire.eu/wp-content/uploads/2016/09/D2.1-MAESTRI-Efficiency-Framework-concept-description.pdf> (2015)
- [19] Lourenço, E.J., Pereira, J.P., Barbosa, R. and Baptista, A.J.: Using multi-layer stream mapping to assess the overall efficiency and waste of a production system: a case study from the plywood industry. *Procedia CIRP*, 48, 128-133 (2016)
- [20] Baptista, A.J., Lourenço, E.J., Pecos, P., Silva, E.J., Estrela, M.A., Holgado, M., Benedetti, M., Evans, S.: MAESTRI Efficiency Framework as a support tool for Industrial Symbiosis implementation. Eds: Candida Vilarinho, Fernando Castro, Maria de Lurdes Lopes. CRC Press, 01/09/2017, Porto, Portugal, ISBN 978-1-351-20617-2 (2017)
- [21] Holgado, M., Evans, S., Benedetti, M.: D4.3 Toolkit for Industrial Symbiosis. Available at: <https://maestri-spire.eu/wp-content/uploads> (2017)
- [22] Silveira Torres, A., Gati, A.M.: Environmental Value Stream Mapping (EVSM) as Sustainability Management Tool. *PICMET 2009 Proceedings*, August 2-6, Portland, Oregon, USA (2009)
- [23] Faulkner, W., Badurdeen, F.: Sustainable Value Stream Mapping (Sus-VSM): methodology to visualize and assess manufacturing sustainability performance. *Journal of Cleaner Production*. 85, 8-18 (2014)
- [24] Alvandi, S., Li, W., Schonemann, M., Kara, S., Herrmann, C.: Economic and environmental value stream map (E2VSM) simulation for multi-product manufacturing systems. *International Journal of Sustainable Engineering*. 9(6), 354-362 (2015)
- [25] Salmi, O.: Eco-efficiency and industrial symbiosis—a counterfactual analysis of a mining community. *Journal of Cleaner Production*. 15(17), 1696-1705 (2007)
- [26] Mirata, M., Emtairah, T.: Industrial symbiosis networks and the contribution to environmental innovation: the case of the Landskrona industrial symbiosis programme. *Journal of cleaner production*. 13(10), 993-1002 (2005)