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Towards Transdisciplinary Research on Industrial Symbiosis Networks

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Abstract: The study suggests more complex and transdisciplinary approach to Industrial Symbiosis (IS) conceptualization and research, one that transcends traditional engineering and ecological approaches. For that purpose, IS is understood not only as technologically-material but also as a social relationship between organizations which are involved in exchange of secondary resources in industrial and non-industrial technological processes. In Industrial Symbiotic Network (ISN) every organization follows its own benefits and at the same time, contributes to benefits of others and ofsociety in general by improvingtechnological, ecological and economical efficiency of a network of organizations. IS takes place within ISNs of various complexity. Nodes in ISNs can be conceptualized as social actors and links between these nodes are not only technological, material and economic but also social. To introduce the approach, this study first describes key IS terminology, brief history and demonstratesits the main benefits with three well known examples of best practice. These best practices are utilized to demonstratethe importance of social actor's involvement in ISNs in their industrial or non-industrial technological processes. The article concludes with the outline of a transdisciplinary research programme for IS research.

INTRODUCTION

In the last decades, achieving effective management of primary raw materials through reuse of secondary raw materials is a growing trend in the global market for organizations. This is to achieve bothnational environmental policies (or even international as in the case of the European Union policies or Paris agreement) and to achieve increasingly overlapping economic, ecological and social goals. Ecological benefits include reduced air pollution, water and energy consumption whereas economic benefits are provided through savings in supplying raw materials and inmanaging secondary raw materials and in becoming competitive onlocal, regional, national or international market. On the other hand, social benefits are exhibited through creation of new jobs, development of local communities and geographic regions and a cleaner environment for local communities or geographical regions.

Concurrent achievement of ecological, economic and social benefits provides grounds for Industrial Symbiosis (IS) which in the global world represents an extremely important and sustainable mechanism for the reuse of secondary raw materials in both industrial and non-industrial processes. IS is regarded as relationship between three or more organizations which we understand also as social actors involved in direct or indirect exchange of secondary raw materials, i.e., material, water or energy commodities, mainly waste and by-products, achieving synergies between the social actors. In a dyadic relationship, these resources flow from one social actor which would previously have discarded the unused resources to a landfill or release to the atmosphere or water, to social actor which can use these resources as a substitute or primary resources[1]. In this mutually dependent relationship, every social actor while achieving their own benefits, contributes to the prosperity of other social actors and, consequently, to the welfare of society at large[2].

Industrial symbiosis may be a subject to one or more Industrial Symbiosis Networks (ISNs). ISN is a network of industrial and non-industrial organizations and can be formed on local, regional, national and/or international level. In ISN the nodes are organizations, social actors and the links between the nodes represent (oftentimes mutual) cooperation between social actors. ISN can function as closed networks, connecting a certain number of social actors taking part in the network. However, ISNs can collaborate with other ISNs operating as open industrial symbiosis networks in this case, every social actor is also included in a number of industrial symbiosis networks and the networks themselves can evolve to become increasingly complex. In ISNs, indirect social actors (e.g., policy makers, network moderators, experts and consultants) can play a very important role in addition to direct social actors exchanging resources, although they are not considered providers or actors requiring secondary resources.

Examination of ISNs from the technological, economic and especially, ecological point of view has been and continues to be the subject of numerous studies which mainly focus on waste management, industrial ecology[3, 4], circular economy[5], supply chain management[6], economics[7] and information science ontology[8]. These ”traditional” approaches are to an important extent search for answers to particular research questions dealing with technological, economic and ecological efficiency of issues of IS and to en important extent fail to properly account the importance of social aspects of IS and ISNs, although, these aspects could have a profound impact on dissemination of IS as a relevant alternative or potential “hegemonic discourse”[9] in industrial policy and on formation of ISNs[10]. The main purpose of this article is to provide an overview of current debate on the issue and to propose a transdisciplinary research programme on IS, contributing to development of modern industrial symbiosis networks and enable pursuit of future industrial symbiosis goals.

In comparison to economical and ecological aspects of industrial symbiosis networks, explicit scientific research on these networks in terms of social sciences has not received much interest, resulting in the lack of understanding regarding socio-cultural factors involved in creation of these networks and regarding connections between structural and relational characteristics of industrial symbiosis networks. Consequently, the opportunity has arisen to select a multi-disciplinary sociological approach to studying industrial symbiosis networks and to perform a research on implementation and structuring of industrial symbiosis networks under the influence of certain socio-cultural factors.

In its first part, the study tries to delimit of the concept of industrial symbiosis and industrial symbiosis network and briefly describes the historical view of industrial symbiosis. Next, we outline the key benefits of industrial symbiosis and support our assumptions by three of the most famous examples of industrial symbiosis best practice. In the end the research foundation of the thesis is presented alongside the current state of development.

CONCEPTUAL FRAMEWORK

Industrial symbiosis: In nature, symbiosis or coexistence is defined as relationship between two types of organisms (animals or plants) in which these organisms intermittently or continuously cooperate with each other. An organism lives in symbiosis with other organisms and in this relationship each of them benefits from the other. In this case, symbiosis is based on the concept of mutualism where at least two different types of organisms exchange sources of material, energy or information for mutual welfare[11]. Examples of such symbiosis include fungi and trees which are connected through roots to enable exchange of nutrients; moss; bacteria in the digestive system of ruminants or hermit crabs which transport sea anemones on their shells. Wilfing explains symbiosis as a living community which provides benefits to all creatures involved and which is based on mutual assistance in the kingdom of animals and plants.

Industrial symbiosis takes place in social milieu and is mainly addressed in light of opportunities it offers for exploitation of technological, ecological, economic and social synergies. Different researchers Chertow[12], Howard-Grenville and Paquin[13] and Gingrich[14] define industrial symbiosis as an approach to industrial ecology as a synonym for industrial ecology[15] as a subset of industrial ecology[7] as activity in the industrial ecosystem as eco-industrial symbiosis which represents local or regional circular economy and environmental approach[16] and as one of the levels of studying industrial ecology. Deutz[1] sees industrial symbiosis as a stream of untapped resources (byproducts or even waste materials, water and energy). These secondary resources flow from organizations that would have discarded them, to organizations that use them as input to their own production. Chertow[12] defines industrial symbiosis as a collective approach to winning a competitive advantage which involves the actual stream of materials, energy, water and by-products between social actors in different industry sectors. In this interdependent relationship each of the social actors benefits while at the same time contributing to the prosperity of other social actors and society as a whole[2]. In this respect, industrial symbiosis represents the relationship between social actors which are involved in exchange/purchase of secondary resources, i.e., material, water or energy resources and where exchanges/purchases represent synergies between these actors.

Industrial symbiosis between social actors can be established in the form of exchange or purchase of secondary resources. The principle of exchange is used when both social actors exchange secondary resources and material streams in both directions. On the other hand, we purchase is when one social actor sells secondary resources to the other actor and the latter pays for these resources. In this case, we have material flow in one and symbolic flow (money) in the opposite direction. Industrial symbiosis based on the sale of secondary resources is explained by Holm[17] who describes the concept of industrial symbiosis as a common and symbiotic relationship between two or more social actors where the waste of one social actor is purchased by another social actor who utilizes them for their production. Chertow[12] has also defined a criterion for the existence of industrial symbiosis. The criterion requires that at least three social actors are involved in exchange of at least two materials.

Historical overview of industrial symbiosis: Although, humanity has traditionally to a certain extent re-used waste materials, IS was first conceptualized as such in the period before the Second World War. One of its first occurrences is found in the field of economic geography. In 1934, American geographer Almon Ernest Perkins was the first to mention the concept of industrial symbiosis in his article “The Geography of American Geographers” which was published in The Journal of Geography[18]. A somewhat more specific definition of industrial symbiosis was described by American economic geographer Walter G. Lezius in his article “The Geography of Glass Manufacture at Toledo, Ohio” which was published in the Journal of Economic Geography in 1937[19]. However, the formal development of industrial symbiosis again within the paradigm of economic geography began only after the Second World War. In 1947, American geographer George Renner described organic relations between sectors from an ecological point-of-view[20]. Based on the production of waste and by-products and their stream between industry sectors, he described the potential for a company to deliver its waste to another sector where waste will be used as raw material. Renner named this relationship industrial version of symbiosis as it occurs in the ecosystem[20]. Although, he was speaking of activities and functions of industrial symbiosis, he had not yet used the term “industrial symbiosis”. In 1967, the president of the American Association for the Advancement of Science wrote about existing examples of industrial symbiosis where one industry sector neutralizes, or uses, the waste from other industry sectors[21].

Year of 1989 is a landmark year for industrial symbiosis as it represents a time when the first research and examples of industrial symbiosis[12] began forming. In the same year, the Kalundborg case study began in Denmark where companies or social actors, in conjunction with their local authorities, developed a complex network for the exchange of waste materials which have the potential to be reused in industrial processes as raw material[22]. Today, the Kalundborg case study is arguably the best known example of industrial symbiosis and serves, together with subsequent case studies as a validation of ecological, economic and social benefits of industrial symbiosis. This does not imply that IS did not exist before that, though. Preliminary forms of industrial symbiosis developed early on after industrialization of production and involved both mutual exchange of material goods as well as purchases of by-products and waste materials. However, this occurred on a much smaller scale. Development, since, 1989, both in the area of industrial and environmental policy-making as well as in research on the topic, brought prominence to IS and ISNs. However, it is fair to say that we are still in the early stages of exploitation of various benefits of IS, its policy-making aspects and especially in terms of more comprehensive and transdisciplinary approach to scientific exploration of this phenomenon.

Industrial symbiosis networks: IS takes place within one or within several ISNa which are mutually interconnected by one or more nodes and thus cooperate with each other, forming larger and more comply networks. Accordingly, it can be examined within one or several industrial symbiosis networks. As with other types of networks such as mathematical, technological, informational or social, industrial symbiosis networks can be described using network theory. In mathematical formulation, the network theory is supported by graph theory, thus, the network can be described or represented in the form of graph: G = (V, E) where V is the set of points or nodes (Vertices) and E is a set of (undirected or directed) lines[23]. The nodes(N) of the graph represent units within the network while their connections represent relations between these units (ibid.). The graph is displayed as an image with the nodes illustrated using circles, undirected connections illustrated using line segments and directed connections using arrows connecting the nodes (ibid.). Networks containing some 10 nodes and connections are classified as small networks, networks with some 100 nodes and connections are classified as medium-sized networks and networks with some 1,000 nodes are large networks (ibid.). On Fig. 1, the left illustration shows an example of a small undirected network whereas the one on the right is an example of a small directed network (N = 6 and E = 10).

Industrial symbiosis networks are directed networks in which nodes represent social actors and connections represent cooperation between the actors. Cooperation between social actors in ISN is accomplished by four types of flow: information, material, financial and knowledge flow. Information flow is the first to be established between social actors and is crucial for establishing material flow. When a social actor sells secondary resources, we have material flow in one direction and financial flow in the other direction. If two social actors are involved in exchange of secondary resources, we illustrate material flow in both directions. Knowledge flow is also a two-way stream and helps social actors identify good practice and exchange experience and expertise. The largest group of social actors in direct material flow is represented by industrial companies which have access to waste secondary resources and industrial companies which require secondary resources.

In addition to direct social actors, another key role in industrial symbiosis networks is attributed to those indirect social actors which neither provide or require secondary resources. These so-called (online) exchanges act as a link between providers and seekers of secondary resources by providing information to and about other

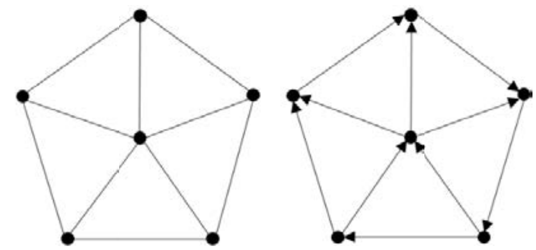

Fig. 1: Examples of a small undirected and small directed network

social actors as well as identify and promote solutions in the field of industrial symbiosis. Such example is an internationally acclaimed and first-ever National Industrial Symbiosis Programme (NISP) in the UK, the purpose of which is to find solutions for processing industrial waste into raw materials. NISP was developed in 2003 from three pilot projects in Scotland and included over 15.000 μ, small and medium-sized companies from different industry sectors[24].

Industrial symbiosis can take place within a single industrial symbiosis network with a certain number of social actors taking part in the network and only providing services between themselves. In this case, we are speaking of temporarily closed networks which can be either small or large. On the other hand, industrial symbiosis networks can also cooperate and in this case we classify them as open industrial symbiosis networks. As a general rule, social actors from open-type industrial symbiosis networks cooperate in more than one network. On Fig. 2, the left illustration shows an example of a medium-sized directed industrial symbiosis network (N>100 and E>100) whereas the one on the right is an example of a large directed industrial symbiosis network (N>1000 and E>000).

Industrial symbiosis networks exist on local, regional, national and international levels. Chertow[12] claims that geographical proximity of actors is the pre-condition for implementation of industrial symbiosis. In other words: social actors involved in direct flow of secondary material resources must be located nearby. However, this depends on economics of specific exchange, linked with logistical costs. Furthermore, social actors taking part in industrial symbiosis network but who are not directly involved in material flows, geographical proximity is not as important, especially due to recent development of ICT tools for management of ISN networks. Figure 3 shows an illustrative example of a small, elementary industrial symbiosis network, typical for the local level within a statistical region.

The example above represents an industrial symbiosis network consisting of four social actors, involved in direct

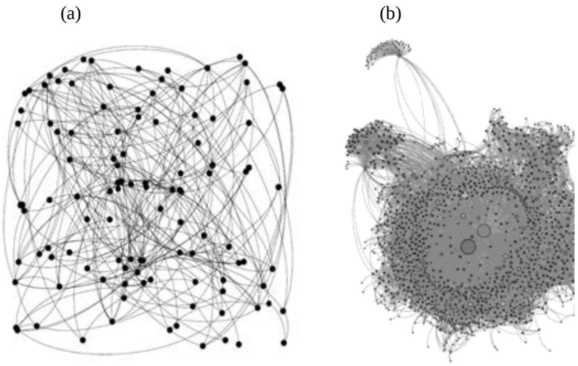

Fig. 2(a, b): Examples of medium-sized and large directed industrial symbiosis network

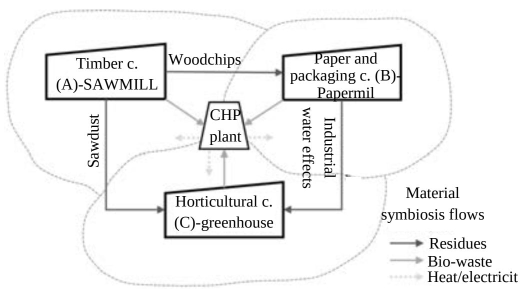

Fig. 3: Example of a small/elementary industrial symbiosis network

symbiotic material flows. Woodworking company sells their woodchip wasteto a paper mill which uses them as input material for manufacturing paper. At the same time, the woodworking company sells wood sawdust to a gardening company to be used as material for mulching plants. Conversely, the paper mill sells their waste water to the gardening company to be filtered and used for watering plants. In turn, the woodworking company, the paper mill and the gardening company sell the biological waste they generate to a heating plant and a power plant. In accordance with established procedures, the heating and power plant then use biological waste to produce heat or electricity, for example to heat a swimming pool or apartments in residential blocks. This example illustrates how two social actors can be involved in more than one symbiotic material flow.

BEST PRACTICES IN INDUSTRIAL SYMBIOSIS

When speaking about the general benefits of industrial symbiosis, we principally focus on the 5 key benefits as they are described in detail by Lombardi and Laybourn[25]. By their account, implementation of industrial symbiosis increases ecological innovation, creates new jobs, initiates green growth, streamlines business processes and encourages exchange of best practice. Moreover, through re-use of secondary resources in industrial and non-industrial processes, industrial symbiosis creates synergies and after a period of time results in different ecological, economic and social benefits. In light of ecological benefits, its main goal is reducing the amount of waste, our dependence on non-renewable energy sources, emissions and greenhouse gases. By reducing the amount of secondary resources which would otherwise have beendisposed of, i.e., waste, representing a burden to the environment in the long-term, the natural environment is preserved by encouraging industrial symbiosis. Another ecological benefit of industrial symbiosis comprehends mitigation of climate change as stated by Peter Laybourn, founder of International Synergies Ltd.[26]. Table 1 shows ecological benefits of industrial symbiosis which serve to mitigate the rise of climate change.

Industrial symbiosis also entails economic benefits for social actors involved, e.g., savings in purchase of new materials, savings in management of secondary resources, savings in production cost and additional revenue from re-processing secondary resources into by products and primary resources. Hence, economic benefits in the form of financial savings through implementation of industrial symbiosis are based on reduction of various types of costs which include cost of material, energy-related costs, waste-management costs and costs of environmental legislation compliance. Economic benefits also include development of synergies between production and distribution in order to diminish the non-renewable energy source market's dependence and social actor's increased competitive advantage.

Indirectly, ecological and economic benefits together result in social benefits, e.g., in creating new jobs, improving the quality of jobs, preserving existing jobs, the appearance of new social actors and the cooperation between social actors, developing local communities and statistical regions and ensuring a cleaner environment. In the broader sense, implementation of industrial symbiosis also contributes to realization of sustainable development objectives. In this respect, Laybourn [26] highlights five key objectives. The first objective in realization of which industrial symbiosis has an important role is to promote sustainability including sustainable economic growth and productive employment and ensuring employment for everyone[26]. The role of industrial symbiosis in attaining the second objective is in the promotion of sustainable industrialization and innovation in attaining the third objective that of ensuring sustainable consumption; the fourth objective that of climate change mitigation and the fifth objective is supported by industrial symbiosis by means of raising funds for implementation and revitalization of the global partnership for sustainable development[26].

Table 1: The impact of industrial symbiosis on mitigating climate change

Ecological benefits of industrial symbiosis	Mitigating climate change by implementation of industrial symbiosis
Industrial symbiosis→Ecological benefits→Climat change mitigation	
Preserving input resources	Low energy consumption during processing of secondary resources
Shorter processing time	Using renewable energy sources reduces consumption of fossil fuels, electricity and other resources
Use of alternative fuels	Replacing fossil fuels with alternative non-fossil fuels in industrial processes
Lower cost of transportation	Less activities requiring transportation
Lower cost of waste management	Decreasing amount of waste on landfills and disposal facilities
Lower cost of energy	Producing energy through industrial symbiosis

Examples of best practice: Kalundborg case study is considered one of the earliest and most famous examples of best practice in industrial symbiosis in the world. Kalundborg is a small harbor town on the northwest coast of the largest Danish island of Sjælland in Denmark. The case study began in 1961 as water management project. Because supply of fresh water in Zealand region, where Kalundborg is located was not always available, the local authorities decided to install a pipeline for the new refinery to provide the refinery with water intake from Lake Tisso[4]. In 1981, Asnæs thermal power plant began supplying Kalundborg with steam for heating new neighborhoods. Soon afterwards, the system was extended to Statoil and Novo Nordisk towns (ibid.). The steam-driven heating system from the thermal power plant had replaced about 3,500 oil furnaces which would otherwise have represented a significant source of air pollution (ibid.). The thermal power plant uses sea water for cooling, thus, reducing the use of fresh water from Lake Tisso. The plant feeds part of the hot salty water which is produced as a by-product in the process of cooling, into 57 ponds of the nearby fish farm (ibid.). Consumption of fresh water for cooling is also reduced by using pre-treated water which is supplied by Statoil oil refinery and amounts to approx. 1 million cubic meters of water per year (ibid.). In turn, the refinery supplies its excess gas to Gyproc company after observing a flame at the top of the refinery and the burning gas, the company quickly identified it as a potentially cheap source of energy (ibid.). Novo Nordisk pharmaceutical company sells biomass, produced as by-product in their industrial process, to local farmers to be used as fertilizer (ibid.).

In “Terra Nitrogen and John Baarda” case study, the team from National Industrial Symbiosis Programme (NISP) in the United Kingdom used data mapping to identify and carry out one of the most successful synergies in the field of agriculture in the UK. The case involves processing, diversion and re-use of 12,500 tones of CO_2 per year. In this process, nitrogen manufacturer and vegetable producer have the key roles (ibid.). NISP has provided a link between both social actors and enabled them to conclude a deal which ensures that 12.500 tons of CO_2 from Terra Nitrogen factory are fed into the 38-acre greenhouse in which John Baarda grows over 300,000 tomato plants throughout the year (ibid.). The greenhouse which is the largest complex of its kind in the UK was the first to use industrial waste products as primary source of energy (ibid.). CO_2 that is produced in the factory is a key component for the growth of tomatoes and increases tomato production by half while reducing industry-related CO_2 emissions (ibid.). The steam which is produced by Terra nitrogen factory and had previously been dissipated into the atmosphere is now after establishing industrial symbiosis being converted into hot water used to heat the greenhouse as large as 23 football fields (ibid.). In this way, John Baarda benefits from lower electricity bills, while further reducing production costs and ensuring stable crop production even during the winter (ibid.). The project, we have described above represents a tangible incentive for British agriculture, because the UK would have to import tomatoes from Spain during the cooler months (ibid.).

Another project “Home Sweet Home If You Have One” by National Industrial Symbiosis Programme (NISP) team in the UK resulted in collaboration between two program members. The project comprises of re-using old, deposited foam products in building low-cost, sustainable housing. The two social actors in this project create more than € 35,000 of savings (ibid.). As a NISP member, the company had participated in research on re-use of foam products for over a year but only found the solution when Globally Greener Solutions (GGS) joined NISP.GGS introduced NISP with its low-energy, cost-effective, mobile and static unit for processing foam materials (ibid.). The unit works by reducing the volume of input waste material, then mixes the material and knead it into an inert substance called Glowasol which can be used in a wide range of manufacturing processes including production of panels for construction of low-cost, sustainable housing (ibid.). Eventually, GGS and Sekisui Alveo developed a new and improved system of waste management to make the waste material suitable for transport to GGS manufacturing plant (ibid.). After taking part of the synergies, GGS has been processing up to 400 tonnes of previously useless plastic waste per year while Sekisui Alveo has experienced significant cost savings in waste disposal and is constantly improving their environmental effectiveness (ibid.).

These best practices are not best practices due to some revolutionary industrial engineering approaches or technological development. If this was the case, dissemination of technology would suffice for rapid development throughout the world. Instead they exemplify that formation of well-functioning ISNs is primarily dimension of the social aspect. Other research based on multi-criteria decision decision modeling of successful cases demonstrated definitively that social factors, alongside technological and economic aspects, play important role in establishment of successful ISNs[10]. This should not come as a surprise, since, we have demonstrated the impact of social factors on other aspects of technological innovations[27-29] and applicability of this line of analysis in others, however, in research on IS and ISNs this perspective is poorly developed.

FEATURES OF A TRANSSCIPLINARY RESEARCH PROGRAMME ON INDUSTRIAL SYMBIOSIS

We have mounting evidence that industrial symbiosis provides ample opportunities for a truly transdisciplinary value-added research but this opportunity is still unexploited[30]. Hence, we provide the outline for an international research programme which would not only combine hard and soft sciences in unprecedented ways but would also result in important practical applications, e.g., development of mechanisms for implementing industrial symbiosis into natural, technical and socio-cultural setting. The proposed research programme denotes an transsciplinary research project, dealing with dynamic, complex networks which at the same time exceed the boundaries between and are shaped by the technical, natural, computer and social systems. This is possible because industrial symbiosis networks represent such dynamic, complex networks. In this respect, industrial symbiosis can be defined as sharing services, utility or by-product resources between industries in order to add to their value and to reduce their financial and environmental burden. Consequently, research would also contribute to the study of sustainable industrial ecosystems through interactions and exchanges between industrial flows and surrounding environment where sustainability would gain a broader interpretation than its elementary ecological or environmental definition. It is to be emphasized, however, that this field of research is already steadily gaining ground as the intentional development of novel symbiotic networks consistent with systemic approaches of industrial ecology and industrial symbiosis exhibits a significant potential to reduce dissipation of energy and materials. This potential has lately received the attention of researchers, policy-makers and companies, allowing for new research opportunities.

As any ambitious research programme, the afore-mentioned project should be managed as ground-breaking effort in order to provide well-founded transdisciplinary theoretical and methodological foundations for systematic research on dynamic industrial symbiosis networks. It should aim to develop a theoretical model and adopt novel approaches and analytical techniques that will assist in gaining new knowledge of the underlying foundations of industrial symbiosis and its observable facts for us and other researchers.

Before starting the programme, research enterprise should be divided into two main phases. During the first phase which should comprise critical analysis of the literature and development of new analytical protocols, one should critically review the published contemporary research and analytical techniques and explore ways to significantly improve them for future research. Additionally, one should study the underlying structure of existing industrial symbiotic networks from both quantitative and qualitative perspective, i.e., use quantitative objects to model industrial symbiotic networks and design efficient algorithms for their analysis and visualization and take advantage of qualitative research not only to fill any gaps but to explore completely new ideas and hints.

In the second phase, the newly developed analytical techniques should be substantiated by reliable data from several countries, if possible. This would allow for analysing the robustness of analytical techniques for investigation of networks in different stages of development. Currently, the UK is the only country in the world with a well-developed and functioning National Industrial Symbiosis Programme (NISP). On the other hand, there are some but still relatively few countries where industrial symbiosis networks are emerging in the early stage and a number of countries that display no such systematic efforts and only accommodate spontaneous small-scale networks. However, this could change in the future. The countries with no systematic effort can provide us with particularly interesting cases for research on embedding industrial symbiosis networks in environmental, technical and socio-cultural settings. Slovenia, for example can provide such an intriguing case. It produces >1.9 million tons of residential and commercial waste annually which includes more than 4000 tons of hazardous waste, its annual volume steadily increasing. Currently, >50% of this waste is disposed of on landfills. In the future, this is expected to change, as the country's priorities are set to addressing the use of waste in accordance with Regulation 2150/2002/EC (The European Parliament and the Council of the European Union on Waste Statistics in 2002) with the goal of increasing the use of clean technologies, defining appropriate product design and recovery and energy use.

From this point-of-view, small country like Slovenia can provide an excellent testing ground for new research methods.

The general objective of such a project would be to connect mathematical theory (discrete mathematics, networks, statistics) with other disciplines (sociology, computer sciences, environmental studies) and develop tools for research, analysis, design, optimization and modelling (computational modelling) of dynamic, complex industrial symbiosis networks, i.e., their structure, dynamics and properties and to determine how their interaction with technical, natural, computer and social systems helps in shaping them. The research programme would also pursue other more specific objectives:

- Review and consolidate contemporary knowledge and research methods on industrial symbiosis, including industrial symbiosis practice, procedures, frameworks and guidelines as well as review scientifically verified technologies enabling these processes (decision supporting technology, ontology engineering, social networking and user-centric technologies)
- Establish rigorous system-theoretic and theoretical foundation and research methods for analysis of complex industrial symbiosis networks by exploring applicability of mathematical network analysis
- Elaborate knowledge models and knowledge methodologies capable of capturing and processing knowledge and information in industrial symbiosis networks, focus specifically on development of computer ontologist required to manage and facilitate industrial symbiosis implementation
- Investigate the reciprocal structuring communication of industrial symbiosis networks with the technical, natural, computer and social systems

Last but not least, a comprehensive research programme should emphasize the role of social systems in shaping the dynamics of industrial symbiosis networks, i.e. how combinations of relevant actors (social networks), institutions (multi-level environmental and industrial policy and practice) and cognitive frames (public perception) impact their structuring.

Another relevant question is that of key research networks the research programme would employ. Industrial symbiosis networks are complex grids which at the same time exceed the boundaries of and interact with the technical, natural, computer and social systems. In order to ensure that project objectives are achieved, the programme should apply research methods which exceed disciplinary boundaries and enable analysing the structure of relationship between significant varieties of entities and use discipline-specific methods, when necessary, to reach specific objectives. Our hypothesis assumes the main research methods, described below.

The core research method used could be mathematical network analysis. This method would allow inter-disciplinary exploration and would encompass networks from technical, natural, computer and social systems. To employ the method meaningfully, we should, as argued above, acquire data for network analysis through selection of waste streams in several countries in different stages of development. Tools for network analysis and visualization and combinatorial optimization will be especially, important in this phase.

Secondly, one could adopt the fuzzy-set analysis a type of qualitative comparative research method to explore the impact of social networks, institutions and cognitive frames on industrial symbiosis networks. The key research question here should be to determine whether these social impacts are necessary and sufficient conditions for successful establishment of an industrial symbiosis network. Research should also explore the potential variety and stability of these causal conditions.

Finally, researchers could use various supporting methods such as secondary document analysis (online) surveys, focus groups and structured interviews, to collect the less systematic and qualitative data.

What is the originality of such a research programme? The proposed research programme falls in the framework of predominantly transdisciplinary research and deals with a topic only recently discovered by researchers and institutions from various scientific fields and industries. As such, the project has the potential to extend beyond the “current state-of-the-art” in the freshly developing field of industrial symbiosis research. Its main contributions to science will be.

We will make significant headway in the recently established field of research less than a quarter of a century old itself with the goal of developing strong theoretical foundations as well as adopting a wide variety of research methods.

In this research programme, transdisciplinary will not represent a buzzword only. Using mathematical network analysis, researchers will strive to integrate the perspective from industrial, natural, computer and social systems into one analysis, hypothesizing that industrial symbiosis networks are shaped by specific topographies of these four systems.

Most importantly, industrial symbiosis as a field is currently managed mainly by skilled practitioners which also applies to network mediation. Science still has to make a contribution, if this field is to be developed further. Symbiotic links admittedly constitute a complex task that involves background knowledge from various disciplines. There is a need for considerable upgrade of industrial symbiosis towards a systematic and powerful field of exploration which would attract both scientific community as well as to the public.

CONCLUSION

The purpose of industrial symbiosis networks is to build collective flows among plethora of actors leveraging the exchange of resources to benefit both, their production efficiency and its environment by reducing carbon footprints, minimizing landfill waste and saving non-renewable and fragile resources which should be taken into account by any programme. Industrial symbiotic networks exist to exchange resources, e.g., by-products, assets and services, through closed and sustainable life-cycles and supporting sustainable operation. Local co-operation in industrial symbiosis reduces raw material use and waste disposal, while material and energy flows extending outside the boundaries of networks increase system entropy and provide considerable positive environmental impacts. The low cost of waste also brings tangible economic benefits to members of industrial symbiosis networks. These networks emerged as a collective, multi-industrial approach to improve economic and environmental performance through the use of wastes and by-products as substitutes for raw materials.

However, in spite of these promising benefits industrial symbiosis networks in most environments are under-developed and the rationale behind their operations has not been systematically researched. As a consequence, both policy makers and industrial participants are unaware of the benefits that the establishment of such networks provides. We conclude with a few practical considerations.

Firstly, it is acknowledged that the key to success of the entire project is embedding the industrial symbiosis in the region. Examining industrial symbiosis is not only relevant from a scientific perspective but also in terms of policy. It is very important that businesses and relevant regional and national policy-makers are involved in all attempts at forming industrial symbiosis networks during project implementation phase. The process of their involvement in the project has to be practical, evidence-based and tailored to the needs of businesses and policy-makers.

This implies that one of the key challenges is to develop tools for creating integrative, adaptive industrial symbiosis awareness and initiative to produce a viral effect of spreading industrial symbiosis in the business community. This model should take into account knowledge developed and assimilated through aforementioned research programme and also identify social, political and other relevant, although, intangible, bottlenecks limiting implementation of industrial symbiosis such as lack of cooperation and trust between businesses and policy-makers, legal constraints on environmental results, absence of awareness of industrial symbiosis and industrial process and otherwise related environmental consequences, lack of resources etc. Adaptive implementation model should be based on “what works” or evidence-based policy. It should at least involve raising awareness and initiative, assessment of the situation and creating vision, building consequences and commitment, improvement of policies and strategy and implementation and continuous assessment of improvement. The goal is to develop a unified industrial symbiosis implementation model that would represent a generic framework but would be adaptive enough to also consider context-specific nuances and needs. This model will become an integral element of the policy process and will serve as basis for development and implementation of industrial symbiosis.

Finally, the purpose of this research and policy-making effort should be to maximize the utilization of existing resources. We would like to stress that IT can and will play an increasingly important role in this process. Efforts in embedding the new industrial symbiosis paradigm must include application of the relevant IT resources. Special consideration has to be made as to whether these resources incorporate products of the future research programme. In this respect, IT resources not only include industrial symbiosis-specific services that will be developed some are already being developed but also utilize a variety of Wikis, online workbooks and existing social networks. Hence, any policy-oriented research will also analyse applicability of research on the popularity of social networks, including, Facebook, Twitter, LinkedIn, Instagram, etc.

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REFERENCES

01. Deutz, P., 2014. Food for Thought: Seeking the Essence of Industrial Symbiosis. In: Pathways to Environmental Sustainability, Salomone, R. and G. Saija (Eds.)., Springer, Cham, Switzerland, pp: 3-11.
02. Manahan, S.E., 1999. Industrial Ecology: Environmental Chemistry and Hazardous Waste. CRC Press, London, England, UK.,.
03. Chertow, M.R., 2000. Industrial symbiosis: Literature and taxonomy. Ann. Rev. Energy Environ., 25: 313-337.

04. Ehrenfeld, J. and N. Gertler, 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. J. Ind. Ecol., 1: 67-79.
05. Laybourn, P., 2016. Facilitated industrial symbiosis: The circular economy in action. International Synergies Limited, Birmingham, England.
06. Leigh, M. and X. Li, 2015. Industrial ecology, industrial symbiosis and supply chain environmental sustainability: A case study of a large UK distributor. J. Clean. Prod., 106: 632-643.
07. Chertow, M.R. and R.D. Lombardi, 2005. Quantifying economic and environmental benefits of co-located firms. Environ. Sci. Technol., 39: 6535-6541.
08. Cecelja, F., T. Raafat, N. Trokanas, S. Innes and M. Smith *et al*., 2015. e-Symbiosis: Technology-enabled support for industrial symbiosis targeting small and medium enterprises and innovation. J. Clean. Prod., 98: 336-352.
09. Makarovic, M., J. Sustersic and B. Roncevic, 2014. Is Europe 2020 set to fail? the cultural political economy of the EU grand strategies. Eur. Plann. Stud., 22: 610-626.
10. Mileva-Boshkoska, B., B. Roncevic and E.D. Ursic, 2018. Modeling and evaluation of the possibilities of forming a regional industrial symbiosis networks. Social Sci., Vol. 7, 10.3390/socsci7010013
11. Huber, J., 2012. Industrial symbiosis and ecology-inspiration for sustainable industrial systems. EDI. Q., 4: 2-4.
12. Chertow, M.R., 2007. Uncovering industrial symbiosis. J. Ind. Ecol., 11: 11-30.
13. Howard-Grenville, J. and R. Paquin, 2008. Organizational Dynamics in Industrial Ecosystems: Insights from Organizational Theory. In: Changing Stocks, Flows and Behaviors in Industrial Ecosystems, Ruth, M. and B. Davidsdottir (Eds.)., Edward Elgar Publisher, Cheltenham, UK., pp: 122-139.
14. Gingrich, C., 2012. Industrial symbiosis: Current understandings and neede d ecology and economics influences. Ontario Tech University, Oshawa, Canada.
15. Philips, P.S., R. Barnes, M.P. Bates and T. Coskeran, 2006. A critical appraisal of an UK county waste minimisation programme: The requirement for regional facilitated development of industrial symbiosis/ecology. Resour. Conserv. Recycling, 46: 242-264.
16. Hartard, S., 2008. Industrial ecology and industrial symbiosis: New concepts or new branding?!. Umwelt-Campus Birkenfeld (Hochschule Trier) (Umwelt-Campus Birkenfeld), Birkenfeld, Germany.
17. Holm, I.V., 2013. One man’s trash, another man’s treasure. Architectural circuits in a global context. BDC. Bollettino Del Centro Calza Bini, 13: 53-71.
18. Desrochers, P. and S. Leppala, 2010. Industrial symbiosis: Old wine in recycled bottles? some perspective from the history of economic and geographical thought. Int. Reg. Sci. Rev., 33: 338-361.
19. Lezius, W.G., 1937. Geography of glass manufacture at Toledo, Ohio. Econ. Geogr., 13: 402-412.
20. Renner, G.T., 1947. Geography of industrial localization. Econ. Geogr., 23: 167-189.
21. Spilhaus, A., 1967. The experimental city. Daedalus, 96: 1129-1141.
22. Van Berkel, R., T. Fujita, S. Hashimoto and M. Fujii, 2008. Quantitative assesment of urban and industrial symbiosis in Kawasaki, Japan. Asian Environmental Research Group, National Institute for Environmental Studies, Tsukuba, Japan.
23. Wilson, R.J. and J.J. Watkins, 1990. Graphs: An Introductory Approach: A First Course in Discrete Mathematics. Wiley, John Sons, New York, ISBN: 9780471513407, Pages: 340.
24. Anonymous, 2017. International synergies, national industrial symbiosis programme. International Synergies, Birmingham, England.
25. Lombardi, D.R. and P. Laybourn, 2012. Redefining industrial symbiosis: Crossing academic-practitioner boundaries. J. Ind. Ecol., 16: 28-37.
26. Laybourn, P., 2015. Industrial symbiosis: Delivering resource efficiency and green growth. International Synergies, Birmingham, England.
27. Modic, D. and B. Roncevic, 2018. Social topography for sustainable innovation policy: Putting institutions, social networks and cognitive frames in their place. Comp. Sociology, 17: 100-127.
28. Roncevic, B. and D. Modic, 2011. Social Fields of Technological Innovations. In: Global Trends and Regional Development, Genov, N. (Ed.). Routledge, London, England, UK., ISBN:9781136633478, pp: 226-240.
29. Cepoi, V. and B. Roncevic, 2015. Social fields theory explaining innovations and developmental performance: An empirical test. Proceedings of the 4th International Conference on Economics, Political and Law Science (EPLS’15), November 7-9, 2015, Rome, Italy, pp: 38-47.
30. Roncevic, B. and U. Fric, 2015. Researching Industrial Symbiosis: Challenges and Dilemmas. In: Applied Modelling and Computing in Social Science, Povh, J. (Ed.). PL Academic Research, Frankfurt, Germany, pp: 35-49.