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Minimisation of the Resource Demands and Environmental Footprints – the Need for Smart Symbiosis Networks

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One of the ways of simultaneously minimising the use of fresh resources and pollution reduction are the industrial and urban symbiosis, implementing Circular Economy. The resource consumption and release of emissions can be considered as stemming from several domains – product use, production and delivery, resource supply, waste processing and reuse. In the present work, the Circular Economy issues are considered from a structural viewpoint, identifying the need to increase flexibility and the degrees of freedom. The analysis of the motivational example and the strategic issues in industrial and urban symbiosis has shown the need to construct Smart Symbiosis Networks for maximising the sustainability of cities and regions. Unlike previous studies related to circularity and Process Integration, the current analysis takes the holistic perspective and considers all three pillars of sustainability – economic (via cost and profit), environmental (via the footprints) and societal (by embedding health and safety into the analysis).

1. Introduction

Human societies feature two significant problems related to industrial development worldwide. The depletion of natural resources and environmental pollution are caused by the mostly linear workflow applied by contemporary industries. Both effects can be minimised simultaneously by applying Process Integration (PI) methods which combine processes for resource recovery and reuse, minimising the intake of fresh resources and waste release. Several approaches to resource recovery and reuse – Circular Economy (CE) (Hartley et al., 2020), Industrial Symbiosis (IS) (Domenech et al., 2019) and Process Integration (PI) (Klemeš, 2013), bear the promise of substantial reduction of pollution and resource depletion. Under the currently available technologies, the use of resources is related to significant losses – as in the case of energy, which is typically proportional to the release of Greenhouse Gas (GHG) emissions. The magnitude of losses (LLNL, 2021) is in the staggering proportion of approximately 2/3 of all sourced energy economy-wide. Considering that this proportion stays stable for decades and even under the recent push for increased use of renewable energy, the most effective way to contribute to sustainability is to conserve energy, water and materials across the supply chains, as advocated by PI (Klemeš, 2013). The main advantage of this strategy is to reduce the net remaining energy demands and bridging the gap with the capabilities of renewable supply sources and technologies. Varbanov et al. (2020) have proposed an exergy accounting framework using the concept of assets and liabilities to evaluate the overall exergy profit of a process. This accounts for the energy potential of the raw materials and the end products, allowing a broader view of the energy consumption of the supply chain.

Fan et al. (2019) reviewed various options for reducing energy use and environmental pollution, reporting that the synergy of Circular Economy implementations, waste and water management bear the potential for economically feasible solutions. They identified the low data availability, investment and administrative barriers, as well as low stakeholder engagement as the main obstacles in achieving sustainable solutions.

The "European Green Deal" plan (EC, 2020) targets the areas of most intensive material use and pollution. These include electronics, transport, packaging, plastics, textiles, construction and buildings, food.

An important element of bringing about the targeted improvements is the implementation of Industrial and Urban Symbiosis, as demonstrated in (Fan et al., 2021b). There have been many research contributions to Process Integration for pollution reduction – as reviewed by Varbanov et al. (2021) and to Circular Economy – as

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reviewed and analysed by Neves et al. (2019). Industrial Symbiosis has a significant potential for development. Of the cases they analysed, 53 % were from Europe, and significant barriers have been identified – the main being the lack of trust and information among the market actors, administrative problems, and lack of incentives. The main feature of the solutions relates to the improvement of efficiency or pollution reduction of single sites. The few studies at regional scale emphasise a single type of resource or carrier, as Zore et al. (2021) dealing mainly with biomass and Li et al. (2020) focusing on power generation and supply, as well as Fan et al. (2021a) dealing mainly with waste management.
That analysis identifies a knowledge gap – the secondary resources from industrial, municipal, and regional actors need to be considered simultaneously for synergies. The current article makes the stronger case for such a combined consideration, starting with a motivational example and then analysing the strategic issues.

2. Motivational example

Based on the mapping of secondary resources to product and service demands, developed in (Gai et al., 2021b) – Figure 1, the current authors extended the analysis to the comparative evaluation of the trends of the Total Annualised Cost (TAC) on the one hand and the saving of footprints – GHG and Water. The evaluation was performed on a similar case study, exploring the potential of Municipal Solid Waste (MSW) treatment routes for designing circular processes reusing the MSW components. Full details on the case study can be found in the base work dealing with cost and exergy assessments (Gai et al., 2021b) and in the follow-up footprint evaluation study (Gai et al., 2021a).

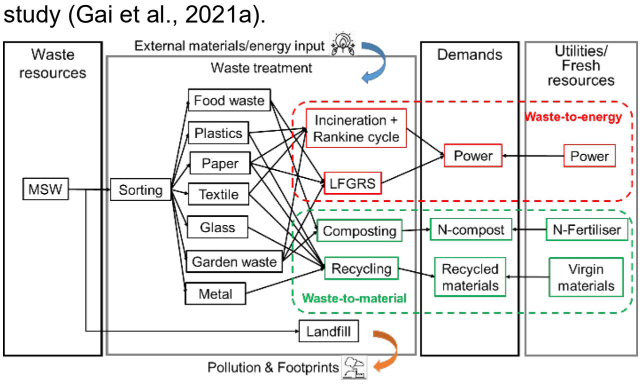

Figure 1: MSW symbiosis system example, after (Gai et al., 2021b)

The main outcomes of the study include the different trends of the TAC and the footprint savings with regard to the degree of circularity, represented by the Total Circularity Index (TCI), as can be seen from Figure 2.

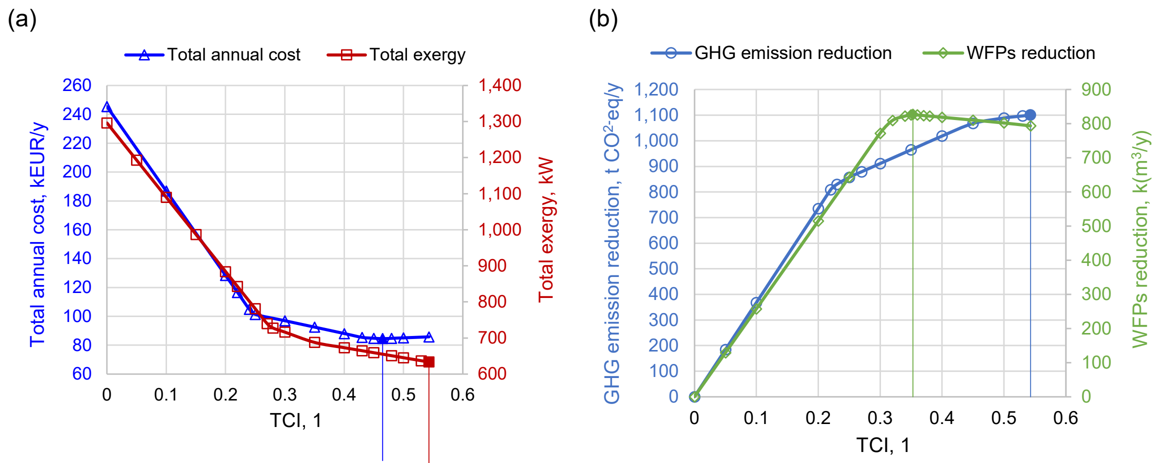

Figure 2: Trends of the symbiotic system performance, after (Gai et al., 2021a): (a) TAC and exergy use trends; (b) Trends of the GHG and WFP reduction

The TCI (Gai et al., 2021b) is a weighted sum of the Circular Material Use Rate and the Circular Exergy Use Rate. Full details are given in (Gai et al., 2021b). One can observe that both curve groups feature extrema – the

TAC curve has a minimum at TCI = 0.465 (1), and the WFP saving curve peaks at TCI= 0.353 (1). While there is some discrepancy between these optima, the common feature is that they take place far below the ideal value of complete circularity – i.e. TCI= 1 (1). This leaves unanswered the question of whether further cost or footprint savings are possible, and if yes – how much? The potential for improvement is obviously there, as nearly 60 % of the MSW still needs to be treated in a different way.

While this specific example is a limited one, it has distinctive structural features that are likely contributors to the limited recycling rate achieved. The first feature is that only a single source of secondary raw materials is considered – the MSW, and within a given availability. Moreover, the pool of users of the potential products and services is limited, also with limited demand. The combination leads to a certain mismatch of what can be recycled, and the remainder is assumed to still be sent to a landfill. Certainly, this is a realistic representation of the current practice in many towns and cities worldwide.

This structural configuration, however, points to the main deficiency of the typical municipal and regional patterns – the isolated consideration and limited interaction between different market and regional actors. This reveals the need to consider the integration of multiple actors jointly and exploiting as many degrees of freedom as possible. This multitude of contexts leads to the need for extensive coordination, which can be delivered only by employing a combination of digital technologies.

Such a combination of multiple actors and even types of actors, with widely varying activities, inputs and outputs, and coordination requirements, leads to the consideration of more complex systems. These systems constitute networks of actors on the municipal, regional and even international markets. The amount of information to be processed and coordinated is vast and would be difficult to coordinate by human actors in real (or reasonable) time, making it necessary to establish Smart Symbiosis Networks with an architecture of the type shown in Figure 3.

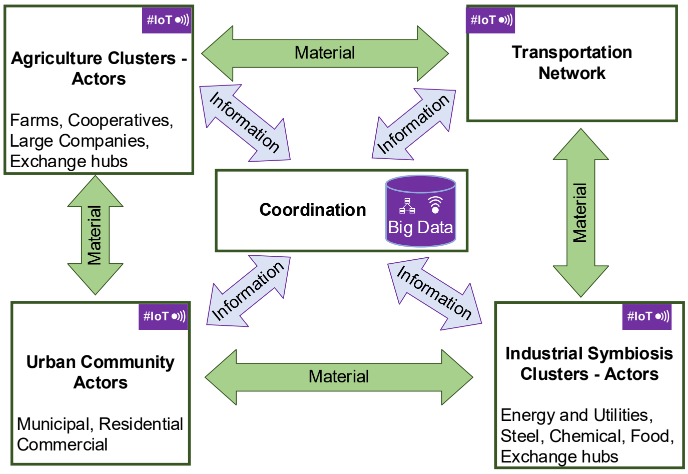

Figure 3: The main actors and interactions of an SSN

Further research has to establish a framework for achieving the goals of maximum economic viability, minimal resource use and footprints, embedding health and safety. The key component of achieving the goal is Process Integration, which has been enormously successful in energy and water conservation. It will be combined with digital technologies for improved accountability (Blockchain) and load tracking (Internet of Things), and targeted symbiosis (Big Data).

3. Analysis of the strategic issues

Industrial Ecology (Frosch and Gallopoulos, 1989) and Industrial Symbiosis (Haq et al., 2021) allow market entities to cooperate by sharing resources (Neves et al., 2020). Li (2018) states that Industrial Symbiosis is a supporting tool in implementing Industrial Ecology. Walmsley et al. (2019) view the concepts of Circular Economy, Industrial Ecology and Process Integration (Klemeš et al., 2018) as equally important, considering the same principle from different perspectives and at different scales (e.g., processes, industrial, urban, regions). There has been intensifying interest in Industrial Symbiosis – as can be seen from the review (Lawal et al., 2021) of the most important works in the last 20 y. The review classified and analysed contributions to the area, including Industrial Ecology, Process Integration, and the development of Eco-Industrial Parks. They analysed the most prominent methods for exchange and recovery of water, energy and materials – Heat Integration, Total Site Integration, Combined Heat and Power (CHP) supply, Mass Integration, Water Integration, CO_2 utilisation,

Carbon Emission Pinch Analysis (CEPA), Total Site Power management. The authors point out the variability and accountability problems as the main knowledge gaps preventing the advance of the symbiosis and integration tools. Combining Urban and Industrial symbiosis is an important step forward in thinking. An investigation of the potential policies for improved eco-efficiency for China (Bian et al., 2020) concluded that the proposed measures could help slow down the GHG footprint increase but not reverse the trend.
Independently, an analysis of the COVID-19 transmission prevention measures has been given in (Brett and Rohani, 2020). The paper reasons that the herd immunity concept has not been successful, advocating the elaboration of the social distancing to be balanced against the need for the society and the economy to function.
Research integrating health and safety, Process Integration, and digital technologies into Industrial/Urban symbiosis, enabling the integration of multiple actors, has been scarce. A report by the World Bank (Kechichian and Jeong, 2016) discusses the importance of Eco-Industrial park features. This is a summary of the opinions of the participants in a World Bank conference. The report discusses environmental and climate issues, energy security, cost, resource use, Green Infrastructure, Clean Energy, financing and implementation issues. In conclusion, the report touches on the need to use smart Information and Communication Technologies (ICT) for enhancing synergy networks, referring to a presentation from the summarised conference. While the circularity and digital components are present in this vision, the Process Integration perspective with its benefits is not part of it.
From the digital technology analyses mentioning Circular Economy, Kunkel and Matthess (2020) discuss the policy expectations and implications of the wider industrial implementation of ICT in Asia and Africa. The societal expectations are directed towards the desired efficiency gains and the concerns from the electronic waste disposal related to the ICT hardware. Another digitalisation tool – Blockchain, is discussed in (Esmaeilian et al., 2020) from the viewpoint of enhancing supply chain sustainability performance without explicitly treating the Circular Economy. The qualitative analysis shows the potential to use Blockchain for accounting schemes, which by implication, can be suitable for footprint accounting.
The health issues of the Circular Economy have been investigated for healthcare supply chains using IoT (Daú et al., 2019). The authors proposed using IoT for closing the material and energy circles of the supply chains. They provide qualitative guidelines for the use of photovoltaics, smart lighting, and water management.
In the perspective paper by Tseng et al. (2018), the Industry 4.0 features are discussed for their potential contributions to improving Industrial Symbiosis. The authors focus on analysis driven by Big Data for information awareness between symbiosis actors. A natural continuation, putting the humans at the centre of the innovation, has been Industry 5.0 (De Nul et al., 2021), aiming to achieve a sustainable, human-centric and resilient European industry. The goal is exactly to embed the wellbeing of the human actors into the process design and operation and to use the technologies for the transition to a sustainable Circular Economy.
Another conceptual paper is by Zhu et al. (2015). It focuses on developing the fundamental definitions, concepts and ideas for making IoT technologies and systems energy efficient and with low footprints. A wider review (Nižetić et al., 2019) analyses the importance of IoT for constructing smart cities. The features emphasised in the discussion include improvement of efficiency and safety of the processes, while IoT is not analysed in the context of more efficient industrial symbiosis.
"SmartSymbiose" (Gemoets, 2021) is a practical online symbiosis platform in Flanders (Belgium). It allows companies to contact each other for the purpose of exchanging input/output flows and minimising the final waste treatment and/or discharge. This is a typical informational node to be included in a proper SSN. While such a node cannot perform the functions of the network, it can be one of its coordination centres.
In summary of the analysis, the existing research dealing with Industrial Symbiosis stop short of combining Process Integration and digital technologies, which is the necessary enabler for a further step-improvement of the symbiosis network performance and delivering SSNs. Applying this combination is essential for achieving lower demands, lower emissions, a stable societal system, and sustainable development.

4. Novel concepts and research necessary

As discussed, the major obstacles to overcome for obtaining successful SSN solutions are: very considerable and still rising demands for products and resources, high losses, stable at 66 - 67 % for decades (LLNL, 2021), high variability of renewables and customer demands, the spatial challenge of integrating renewables and symbiosis actors, and the weak feedback loops created by incorrect footprint responsibility allocation (production-based instead of consumption-based footprint accounting). Adding to these is the low penetration of health and safety measures in industrial and business activities. That analysis leads to a set of inter-related objectives for future research and development.

(i) Formulation of a robust framework for footprint accounting and information awareness of the SSN actors for enabling Eco-cost and Eco-benefit allocation. This aims at having a sufficiently strong feedback signal across supply chains, bringing the economic systems to sustainable development trajectories.

(ii) A step-change in improving the health and safety of the suppliers and the customers involved in the SSNs.
(iii) Minimisation of resource use and environmental footprints – GHG, Water, Nitrogen, PM and maximisation of the economic performance via reduced energy consumption and higher penetration of renewables.
(iv) Minimisation of logistic overheads for materials, goods and people, within the societal requirements.

The large scale in terms of area and number of actors require the aid of digital technologies for sharply increasing the observability, controllability and responsiveness of the SSNs to the variations in demand requirements and the availability of supplies. The hierarchy of the material and energy flows in a Process System, from a Life-Cycle perspective, can be modelled by the Onion Diagram (Figure 4). Each layer represents a group of supply network activities. The product demands to trigger all activities, material, energy, and information flows across the supply networks, ending with the resource and emission burden on the environment. The layers closer to the centre have an increasing influence on the outer layers.

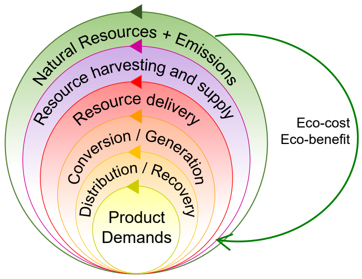

Figure 4: The new Onion Diagram, adapted after (Seferlis et al., 2021)

5. Conclusions

This paper has analysed the potential benefits from industrial and urban symbiosis and the main structural features preventing the further development and achieving a higher circularity rate. The discussion clearly shows the need to increase the degrees of freedom in the system for achieving higher circularity, lower emissions, economically viable activities, as well as higher societal sustainability measured by the health and safety of the people. The main outcomes of the analysis include the need to combine a multitude of actors and widen the system scale, leading to the formulation of the concept of Smart Symbiosis network based on fair allocation of environmental footprints on Life Cycle basis and on digital technologies for optimal and timely coordination.

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