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INDUSTRY 4.0 APPROACHES TO SUSTAINABILITY

Gijsbert Korevaar

Key concepts for sustainability education

- Industrial symbiosis needs design-driven research and education, best done by working on real-live case studies in student teams.
- Circular economy needs insight into the complexity of business model innovation, best taught with serious games and interactive role plays.
- Complex adaptive systems, like circular economy value chains or industrial symbiosis clusters, can best be described with computational tools that enable the practitioners to see the consequences of context, relations, and input settings.
- Industry 4.0 and industry 5.0 need practice-oriented research in strong collaboration with companies and knowledge institutes.

Introduction

The busy bees of our society are the factories that produce all the goods that we need for a modern life. Although industrialization has brought many benefits, it is also threatening the wellbeing of the planet in terms of resource scarcity, emissions, and inequity. On top of that, the main challenge to sustainability is the globality of industrialization. When we take a look at the Sustainability Development Goals (SDGs) as presented by the United Nations (see this hyperlink: https://sdgs.un.org/goals), it shows clearly that all 17 have a close link to industrial development, locally and globally. Some goals are more focused on the direct results, positively and negatively, of industrialization, for example, SDG-6 on clean water and sanitation or SDG-7 on clean energy. Some other goals can only be reached by even further industrialization, like SDG-1 on no poverty and SDG-2 on zero hunger, under the condition of an increasing global population. Other SDGs strongly relate to organization or acceptance of industrialization, for example, SDG-5 on gender equality or SDG-8 on decent work and economic growth.

Industrial revolution 4.0 takes our world forward in recognizing that since the first industrial revolution, which was powered by wood and cheap coal-fired energy in the 1760s, the world has externalized the environmental costs of our industrial production, which has

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resulted in significant levels of environmental destruction and climate change. Industrial symbiosis and circular economy are approaches that have considered the combination of environmental impact reduction and industrial development for many years. These issues present the context in which individually and collectively sustainability education must be considered and developed. They are invariably interlinked and together present some of the most critical resource issues that the 21st century will face, including the scale of environmental impacts that are associated with our increasing production and consumption decisions and the need to consider new paradigms in our economic business models and governance frameworks.

In this chapter the link between industrialization and sustainability is made by using the perspectives of industrial symbiosis, circular economy, industry 4.0, and industry 5.0. Industry 4.0 is another way of mentioning the concept of the fourth industrial wave that is connected to typical sustainability thinking about industrial ecosystems and circular economic systems. Therefore, in this chapter first industry 4.0 is introduced, then industrial symbiosis, followed by circular economy. On all subjects, reflections are made to discuss the importance of sustainability education and how that should look to be ready for a future with even more intense collaboration between human and machine.

Industry 4.0 and sustainability

Industry 4.0 refers to a fourth wave of industrialisation. Current innovations and improvements regarding reduction of the environmental impact of a system are often part of the fourth industrial revolution. Where the first industrial revolution, halfway the 18th century, is about the introduction of steam power, the second revolution is about electricity and mass production. Since the third industrial revolution, starting in the late 1950s of the 20th century, the technological innovation is dominantly about computerization and automation of production. From the start of the 21st century, industry 4.0 is a response to the digitization of manufacturing (Özdemir en Hekim 2018). This means that production can be made more flexible, for example, by using 3D printing techniques, and that production is also more personalized and available everywhere, for example, by using smart logistics and digital twinning of products and services.

More and more publications even continue into an industry 5.0 vision; this will be discussed at the end of the chapter. First, we limit ourselves to developments up to and including industry 4.0. Figure 3.8.1 is taken from a literature review that discusses industry 4.0 in relation to sustainability (Manavalan en Jayakrishna 2019). This figure nicely illustrates what the building blocks are for industry 4.0. The emphasis is on digitalization of production, maintenance, the internet of things (IoT), and supply chains. By making these steps more efficient and by creating more insight in potential bottlenecks, companies can save on energy and resources. Although the digitization and automation might lead to a steep increase in electronic devices, computers, sensors, and data centres, it still can be concluded from many case studies that the potential savings in terms of energy efficiency and resource efficiency outweigh this.

Besides being flexible and adaptive, industry 4.0 is also about the interwovenness of several system perspectives. Industry 4.0 contributes to social fairness, sustainability, and artificial intelligence–driven technologies to increase the efficiency and flexibility of business processes. The challenging issue here is that industry 4.0 certainly is about a vast complexity of big data and system perspectives, but how does that all lead to a regenerative

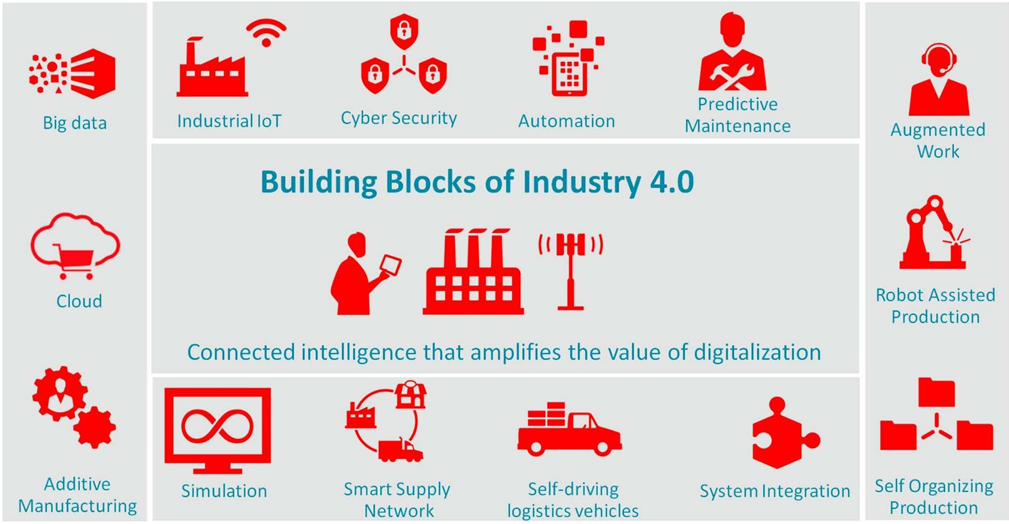

Figure 3.8.1 Building blocks of industry 4.0, taken from (Manavalan en Jayakrishna 2019).

economy that is needed for sustainable development? To answer that question, we first want to introduce two other aspects of sustainable thinking that have taken industrialization into account for many years already, being industrial symbiosis and circular economy.

Industrial symbiosis

From the start of the industrial ecology field, after the idea of 'industrial ecosystems' was launched by Robert Frosch and Nicholas Gallopoulos in 1989 (Frosch and Gallopoulos 1989), quite some attention has been given to eco-industrial parks (Yu et al. 2014). Industrial ecology research and education always has had a strong emphasis on the analytical side of 'metabolism of society', working on tools like life cycle assessment or material flow accounting (Ayres 1994). However, also from the start of the industrial ecology domain, the design of industrial parks or industrial clusters with an exclusive focus on sustainability has received quite some recognition. This focus on the exchange of materials, energy, and information in industrial locations has been labelled *industrial symbiosis* (Jacobsen 2008).

In industrial symbiosis thinking, the relationship between companies is compared to *symbiosis* in ecology. The concept of symbiosis refers to relationships in which at least two unrelated species both gain benefits by exchanging materials, energy, or information. Industrial symbiosis then describes the phenomenon of collaborations between traditionally separate, but geographically proximate, industrial agents to exchange materials, energy, and information for the competitive advantage of these agents, generally leading to environmental and social benefits as well (Chertow 2000).

The most elaborated and well-known example of industrial symbiosis is the eco-industrial park in Kalundborg, Denmark, also known as Kalundborg Symbiosis. This industrial cluster has shown over the years that it can reduce carbon emissions and can save water uptake by intensive exchange of material and energy. It also shows that industrial symbiosis is not only the result of technical innovation but also of strong collaboration between the stakeholders (see Figure 3.8.2).

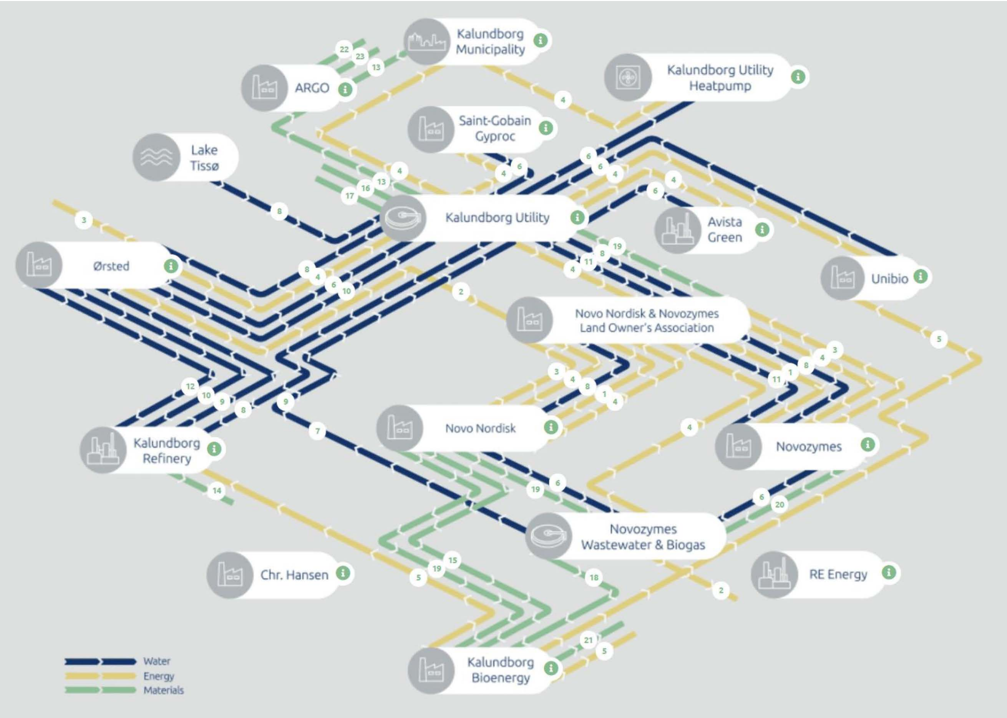

Figure 3.8.2 Kalundborg Symbiosis. Retrieved from https://www.symbiosis.dk/en/ on 31 May 2022.

Kalundborg is an excellent illustration of how a strong facilitator can stimulate exchange and collaboration because the facilitator here is a champion not only in business and engineering but also in social networking and information sharing (Jacobsen 2008). In the publications of Kalundborg Symbiosis it is stressed that the system has a substantial lower carbon emission than comparable industrial clusters, it has a lower intake of lake water for cooling and other processes, and it produces materials at a local level that otherwise should be imported. Overall the sustainability of the system is great example of how an industrial location can perform way above average. Therefore the example of Kalundborg Symbiosis has become an important inspiration for a multitude of industrial symbiosis initiatives in the world. For a good example of how this inspiration has led to many more activities, the reader is invited to take a look at the website and documents of the organization behind the National Industrial Symbiosis Programme (NISP) in the United Kingdom: International Synergies (https://www.international-synergies.com/our-projects/). The NISP initiative stimulated many industrial symbiosis activities throughout the UK and the world, from smaller local initiatives to larger industrial networks.

As an illustration to the global outreach of Kalundborg Symbiosis, an industrial symbiosis activity that is also worth mentioning is the development of the Kwinana Industrial Area (KIA). Located in Western Australia, the KIA is one of the largest documented eco-industrial parks in the world (Rosano and Schianetz 2014). The KIA case study is also mentioned in the report of the World Bank (The World Bank 2021), in which it is stressed particularly that the Kwinana industries show how firm-to-firm industrial symbiosis projects help to increase interaction among tenant firms and bring forward symbiotic opportunities. Public intervention was minimal in this case; all relationships were organically developed with a facilitator, being the Kwinana Industries Council.

In both the Kalundborg and the Kwinana cases, many exchanges between companies are bilateral at first and seem to be not very complicated, like the uptake of waste flows as part of the core processes of a neighbouring facility. However, factories and firms that have worked for some time in industrial symbiosis start to face external and internal factors that are not easy to manage (D'Souza et al. 2015). This increasing difficulty has led to an entire body of literature that describes industrial symbiosis as a complex adaptive sociotechnical system, see for example the publication by Dijkema et al (Dijkema et al. 2015). This means that industrial symbiosis networks can be defined as "systems composed of two deeply interconnected subsystems: a social network of actors and a physical network of technical artefacts" (Dam et al. 2013).

This concept of complex adaptive sociotechnical systems is important in two ways:

1. It helps designers and practitioners to understand and to act upon the complexity in these systems. This is important in education about sociotechnical systems, but also in discussions about topics like industrial symbiosis, circular economy, or industry 4.0 with companies and governments. The understanding of the complexity also avoids the exclusive focus on the engineering side of symbiotic connections, but instead finds a balance with the non-engineering aspects like behaviour, trust, awareness, etc.
2. The approach of sociotechnical systems, with the help of the concept of complexity, supports the way in which these systems can be modelled and studied. Therefore complex adaptive systems, like circular economy value chains or industrial symbiosis clusters, can best be described with qualitative studies on the system dynamics or with quantitative computational tools that enable the practitioners to see the consequences of context, relations, and input settings;

In order to achieve industrial symbiosis and support facilitation of it, several types of dynamics are considered (Boons et al. 2016; Sun et al. 2017). These industrial dynamics support the way in which industrial symbiosis can be understood and applied for the establishment of eco-industrial parks, not only in a technical way (exchange of materials, etc.) but also in an institutional way (for example, agreements, contracts, business models) (Lange et al. 2021a). Figure 3.8.3 shows the key aspects of industrial symbiosis that can be found in many case studies and practical examples:

1. Reduced Environmental Impact – Several indicators are developed or derived from system analysis tools like life cycle assessment to measure the potential environmental impact reduction by industrial symbiosis. Examples are the carbon footprint, water footprint, acidification potential, ecotoxicity, etc. Industrial symbiosis is not about all types of industrial synergies; it has a clear focus on only those synergies that really lead to sustainability. That's why this first key aspect is an essential and determining factor for deciding the potential of industrial symbiosis.
2. Improved Resource Efficiency – Industrial symbiosis mostly considers industrial production directly. Before any type of exchange can take place, it is advised to first find out how the resources can be utilized in the most optimal way. This could be done by finding alternative (bio-) chemical routes, or by valorisation of by-products, or by using the utilities (like clean water, cooling water, solvents, fuels, etc.) as efficiently as possible. Even

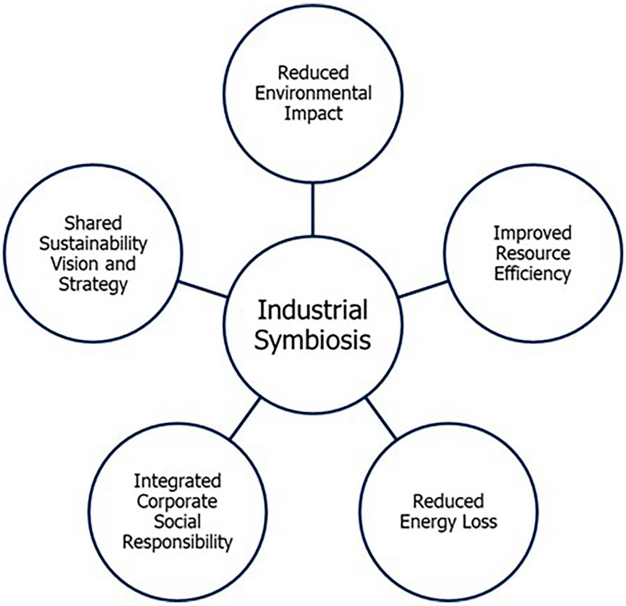

Figure 3.8.3 Key aspects of industrial symbiosis.

when the symbiosis takes place in a business park with little or no production, resource efficiency is still essential, because it directly links to supply chain management or business process optimization.

3. Reduced Energy Loss – Energy production and consumption are the main contributors to greenhouse gas emissions in industrial areas. To implement heat integration or energy integration in order to reduce the use of fossil feedstock or to create more openness to alternative energy feedstock is therefore a key aspect of industrial symbiosis as well. Further on the same arguments apply for the reduction of energy losses as given earlier for resource efficiency.
4. Integrated Corporate Social Responsibility – The first three key aspects focus on the technical performance of businesses, but in order to contribute to the sustainable development goals, non-technical aspects also play a role. Industrial symbiosis can lead to a different local human capital agenda where other skills and capacities are needed. It can also lead to a different relation with the neighbouring urban environment where other impacts are considered. Hence, the corporate social responsibility shall reflect that the company is not only taking measures to reduce the environmental impacts but also works on an alternative economy, resulting in sustainable business models.
5. Shared Sustainability Vision and Strategy – Industrial symbiosis means that companies have an intensive connection with each other and cooperate within an industrial area, or supply chain, or value chain. The symbiosis of physical flows are already mentioned sufficiently, but in order to create sustainable business relations that last for many years, a shared vision and a joint development of a sustainability strategy are also necessary.

Besides the benefit of industrial exchange and the possibility to make that exchange more efficient in terms of resources and energy consumption, industrial symbiosis also has another benefit. It creates the opportunity to connect water, energy, and resources in a systemic way. For water, energy, and food, this has been presented before as 'The Water-Energy-Food Nexus' (Food and Agriculture Organization of the United Nations 2014). This integrative framework applies not only to food networks but can also be applied broadly to various kinds of resources and therefore to industrial networks in general. In particular, the approach of industrial symbiosis is then equipped to design and execute such networks, as is visible already in the Kalundborg Symbiosis.

Circular economy

Circular economy as a term was first coined by David Pearce and Kerry Turner in their book *Economics of Natural Resources and the Environment* (Pearce and Turner 1990). The book proposed redesigning the economic model in such a way that "everything is an input to everything else". With the rise of global consumption and the growth of the global population, the transition to a circular economy becomes more and more urgent. In the World Economic Forum publication about industry 4.0, Klaus Schwab stated:

> At the heart of this promise is the opportunity to shift businesses and consumers away from the linear take-make-dispose model of resource use, which relies on large quantities of easily accessible resources, and towards a new industrial model where effective flows of materials, energy, labour and now information interact with each other and promote by design a restorative, regenerative and more productive economic system.
> *(Schwab 2017)*

From these quotes it becomes clear that the circular economy is the opposite of the linear economy, where resources are extracted and the products are discarded. The evidence of social, environmental, and economic disadvantages against these linear practices are piling up. The global waste production, which is expected to grow to 3.4 billion tonnes per year by 2050, is not only just a materials problem but also related to climate change. If no action towards circular practices takes place, the solid waste management sector is expected to increase its greenhouse gas (GHG) emissions to 2.38 billion tonnes of CO_2-equivalent per year (Kaza et al. 2018). Circular economy aims to create a long-term regenerative economy, that is an economy that is also in balance with ecology and its social context. Circular economy can also be seen as an alternative way to decouple economic growth from environmental impact and resource depletion (Ghisellini et al. 2015).

The circular economy, strongly advocated by the Ellen MacArthur Foundation (Ellen MacArthur Foundation 2013), is an economic and industrial system based on reuse and recycling of products and materials and the recovery capacity of natural resources. Based on cradle-to-cradle thinking by Braungart and McDonough, the Ellen MacArthur Foundation created the so-called 'butterfly diagram' that shows a green side for renewable and biobased materials and a blue side for technical materials (Figure 3.8.4). The two sides of the diagram have different types of feedback loops because in the blue part the materials are always part of the technosphere and should be governed by society at all times. The green part contains materials that are part of the technosphere but also can be part of the ecosphere, meaning that these materials can be treated and transported by natural cycles too.

Circular economy stands for a transition from a linear 'take-make-dispose' model, with raw materials on the one end and wastes at the other, towards a circular model, in which

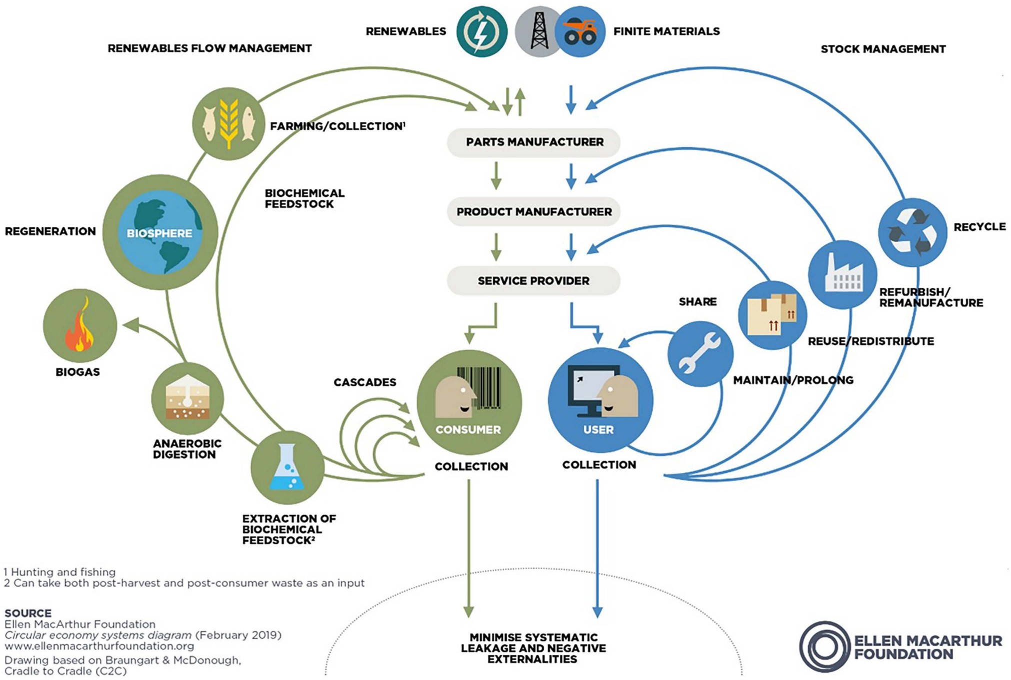

Figure 3.8.4 Circular economy according to the Ellen MacArthur Foundation (retrieved from https://ellenmacarthurfoundation.org/circular-economy-diagram on 31 May 2022).

waste is a resource that is valorised through recycling and reuse. Since industrial ecology can be considered one of the main roots of the circular economy (Lüdeke-Freund et al. 2018), a large communality between circular economy and industrial symbiosis literature is not surprising. Both industrial symbiosis and circular economy are based on the idea of closing energy and material loops in order to make an economically appealing reduction of the environmental impact of industries. This also means that the circular economy design principles overlap with the design principles of industrial ecology. As derived from these principles, circular economy has a strong focus on the development of strategic frameworks, both for the identification of potential closing of the loops and for business support for companies that want to close the loops.

Many companies around the world already have implemented circular economy principles in their business. Examples can be found in the built environment and industrial products, from small to big, from simple to complex. For inspiration and nice illustrations, we like to refer to the book *Products That Last* that offers (according to the title page) “An innovative and practical methodology to unravel product’s afterlife and systematically evaluate if for new opportunities” (Bakker et al. 2014).

In 2021, the World Bank launched the report ‘Circular Economy in Industrial Parks; Technologies for Competitiveness’ (The World Bank 2021) in which the connection is explicitly made between circular economy and industrial symbiosis. Both approaches focus on the practical implementation of sustainability in the industrial setting, but also the circularity of material flows at industrial sites will offer great opportunities for impact reduction and energy efficiency. Circular industrial parks are therefore an important key to a successful implementation of circular economy in the industrial context.

Comparing industrial symbiosis and circular economy

In many academic discussions about sustainability, the attention is drawn either towards the ecological impacts and how they have to be monitored or towards new materials and technologies that can lower the ecological impact. Both approaches certainly add value, but seem to miss one other important aspect, and that is how production and services can transition into a system with less intake of resources, with lower energy consumption, and better environmental performance. These aspects are taken up by approaches as circular economy and industrial symbiosis that aim to support the transition to a sustainable sociotechnical system. In the paragraphs earlier it was mentioned that in this way not only products can be made in a more sustainable way but that especially industrial networks and industrial parks can be designed in a more sustainable way and thus act as a stepping stone for a regenerative industry 4.0 and by that a regenerative sustainable development of the industry.

From the overview provided earlier, we learned that industrial symbiosis is a collective approach in which separate industries create a cooperative network to exchange information, materials, energy, water, and by-products. It is not only about the technical elements but also the softer elements like skilled labour, sustainable strategies, business data, etc., that is exchanged as well. Circular economy refers to the concept that stimulates the circularity of materials, working towards a transition of a linear economy to a circular one. Circular economy is important for sustainable development, mostly because it emphasizes the material side of industrial production as an addition to the climate impact discussion, and it brings in the business side as well. In practice, circular economy is an important concept for regional resource management, taken over by municipalities and countries, because it has this profound notion of economic development.

Modified from the paper by Baldassare et al. (Baldassarre et al. 2019), Figure 3.8.5 summarizes the main components of both industrial ecology and circular economy. In both cases it is about a nested structure that goes from a concept to the practical side. Figure 3.8.5A shows how the academic field of industrial ecology has studied

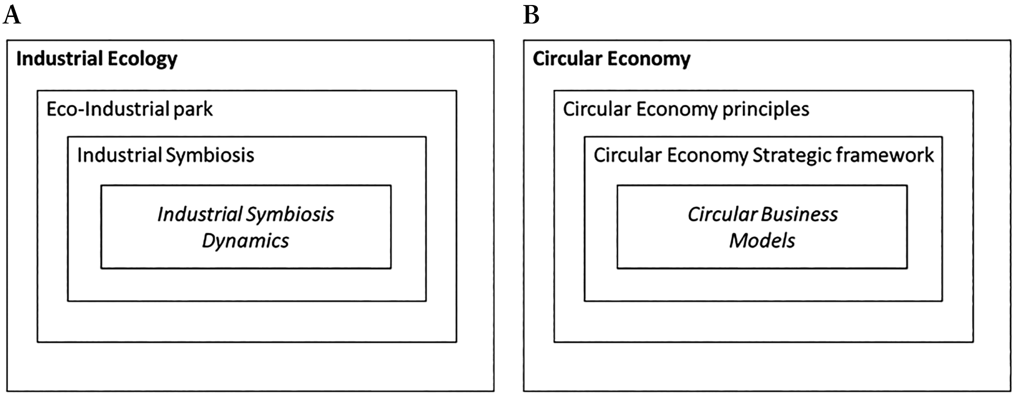

Figure 3.8.5 Nested structures of industrial symbiosis (A) and circular economy (B).

eco-industrial park developments since the beginning of the field. Besides this, industrial ecologists work on many more topics and tools, but in order to turn industrial parks into eco-industrial parks, the tool of industrial symbiosis is very important. And within this concept of industrial symbiosis, the description of how this symbiosis comes about, namely the industrial symbiosis dynamics, is important to steer and understand the transition process.

Figure 3.8.5B shows the same narrative for the circular economy. Here again, we like to emphasize that this is only a limited representation of what topics are important in this field. We describe here only what is needed to come to a transition, which is done by following certain circular economy principles, like those discussed by the Ellen MacArthur Foundation (Ellen MacArthur Foundation 2013). These principles can lead to a strategic framework that combines several insights of the companies and industries that are related to a certain location or supply chain. And within the strategic framework, the business models then lead the industry into a transition to become more circular (Lange et al. 2021a).

Industrial symbiosis, circular economy, and industry 4.0

Industries play a central role in the transition towards the circular economy, since their core activities involve the conversion of materials and energy into finished products and wastes (Ayres 1994). Industries that work towards a circular economy therefore develop business models for slowing, closing, and narrowing resource cycles (Bocken et al. 2016). The main insight of our comparative analysis so far is that industrial symbiosis and circular economy perspectives on sustainability are complementary. We argued that their differences in nature, features, and relevance should be leveraged in combination to get a more thorough understanding of both industrial symbiosis dynamics and circular economy business models. The circular economy perspective is more suitable to start or create a sustainable business operation; the industrial symbiosis perspective is more suitable to study business development over time and its impacts on the environment, the economy, and society. A different way of producing, using, and handling discarded materials is required to make the transition towards a circular economy, to minimize waste, and to maximize resource efficiency. System-level innovations are needed to tackle the mix of values, norms, interests, and motivations of the stakeholders involved.

These aspects of sustainable industrialization are not part of industry 4.0 per se. In many initiatives of industry 4.0 it is shown that production can become smarter, that flexibility is essential, and that social and economic aspects have to be taken into account. But that all can be done with even more use of resources, energy, or production of waste. It is a challenge for engineers and professionals that are also inspired by sustainability to bring the aspects of circular economy and industrial symbiosis into the debate about industry 4.0. It needs careful planning and smart design to work on several innovations at the same time.

This planning and smart design typically comes with the collection of big data and the use of IoT. The industrial development therefore needs to shift from an exclusive focus on production and products to a system in which not only products play a role but also services and the systems that combine several services together. For example, a company that decides to take back the products at their end of life not only has to develop a technology to use the returned products again during production (various types of recycling) but also needs to develop a system to make the taking back easy for customers or other companies in the supply chain. Such a system in practice will require data management of the characteristics of the products, ownership, location, use, etc., and it also needs a logistic or transportation part that enables the tack-back process. Industrial production becomes then more and more interwoven with logistics, storage, data management, etc. This chapter is not the place to discuss all the details of this, but it shows how industry 4.0 can develop into a whole other type of sustainable industry than we ever have seen before.

From industry 4.0 to industry 5.0

So far, we focused on industry 4.0, and the expectation is that this fourth industrial wave will continue for quite some years, but some discussions have already arisen on the next revolution that can be called industry 5.0. From big data and digitalization, the change is towards an industry that is even more focused on the desires of the people, citizens, customers, or employees. Where industry 4.0 is still about more flexibility and more smartness, industry 5.0 will be more focused on a collaborative approach of humans and machines. How this collaboration will shape is quite unclear, and it does not make sense to just present some ideas here on what the future will look like. Although one thing might be said for sure, and that is that industry 5.0 will become even more complex than industry 4.0. The behaviour of customers, companies, or the government; the financial system to support the circularity or flexibility of the economy; the adaptive regulation – all are needed to turn the industrial system into a next level of regenerative sustainability development.[1]

The European Union stated in 2020 that industry 5.0 will be the "economy that works for people". It will be stimulated by several policy initiatives, like the "adoption of a human-centric approach for digital technologies including artificial intelligence" or "resource-efficient and sustainable industries and transition to a circular economy" (Leyen 2019). It is clear that in this way developments such as the stimulation of a green deal, artificial intelligence, and circular economy are all combined, leading to a transition from industry 4.0 to industry 5.0.

Although this development sounds quite ambitious and at this moment not in reach for every economy in the world, it is good to realize what is at stake here. For decades, industrial development has taken its own course based on the latest innovations, inventions, or market demands. The complexity of that development has led to an industrial system that has irreversible impacts on the environment, society, and the economy in many ways. The complexity also shows that we are able to develop such a system in the first place. These two issues, namely the irreversibility of industrial development and the fact that the industrial development is still a human artefact, can help us to find ways to develop the industrial system in other ways. This would require new insights in terms of technological innovation but also in terms of governance of technology and alternative forms of economy.

It addition to new insights, it also requires understanding of the system behaviour in the longer term. What might be the consequences of actions taken today for future opportunities in the market or society? To answer this question, explorations of the future should be made, which is by definition not really accurate, or sometimes simply impossible, but can be supported in many cases by scenario planning.

Scenario planning

The method to explore possible future variations is scenario planning or scenario analysis, most famous from the scenarios that Dutch Royal Shell developed in the last part of the 20th century. Peter Schwartz worked on these scenarios for many years, and his book about how to perform scenario planning is still seen as the start of this method (Schwartz 1991). Scenario planning follows a strict method to ensure that not just personal preferences or blind spots are dominant in possible descriptions of the future. In this way, quite accurate consequences can be described of what currently is important in technological innovation and how these will lead to future development.

This means for sustainability education that students have to be taught about the interwovenness of various concepts and they have to understand how much of the technical innovation is a logical consequence of choices that have been made as a society, in businesses, and by policy makers. On the other hand, it also asks for creativity and smart thinking to find ways to see how these long-term trends can also be influenced towards sustainable development.

Scenario planning is a powerful tool to see the connection between industrial symbiosis, circular economy, industry 4.0, and industry 5.0. In itself the vision of industry 5.0 is actually a scenario, because most of it still has to be realized, but it is a consequence of developments in industry 4.0. But also industrial symbiosis and circular economy can be seen both as a practical implementation of new types of industrial production and a future vision towards which the current industry should develop. Industrial symbiosis can lead to alternative designs of business parks and industrial parks. Circular economy can lead to an entire new portfolio of industrial products with the consequence of different behaviour and alternative economic models. Industry 4.0 can lead to an industry that can much better predict maintenance and have a much more integrated and more efficient supply chain management. And on top of all three, industry 5.0 can lead to an industry and society that are more focused on values creation rather than on just economic growth or material prosperity.

Conclusion

The key message of this chapter is that several concepts are important to talk about with regard to the sustainability of innovative industrial systems. These concepts are therefore also of interest for a regenerative sustainability development. In terms of education, this means a couple of things that have to be taken into account. Based on years of experience in the MSc Programme on Industrial Ecology in The Netherlands, the following lessons learned can be identified.

The behaviour and dynamics of industries are of great importance to the realization of a regenerative sustainability development. Industries manage the intake of feedstock, the production of materials and artefacts, the potential recycling, and waste treatment. Industrial management therefore can break or make sustainable development. Industrial symbiosis, industry 4.0, and industry 5.0 should be aligned in such a way that the industrial development leads to less impact on the environment and even works to restore the natural environment of our human activities.

Consequently, industrial symbiosis needs design-driven research and education, best done by working on real-live case studies in student teams (Baldassarre et al. 2019). Circular economy needs insight into the complexity of business model innovation, best taught with serious games and interactive role plays (Lange et al. 2021a). These two remarks on industrial symbiosis and circular economy stress the need for contextual understanding of the sustainability issues and their potential solutions. In the practice of sustainability education, this means that many examples in class – but also direct relationship with surrounding systems both in industry and urban areas – support the students in becoming active and creative.

From this, it can be see that students and practitioners who have been trained in industrial symbiosis and circular economy can have a substantial effect on the way that the Sustainable Development Goals are reached. Both industrial symbiosis and circular economy lead to higher resource efficiency and improved energy efficiency, resulting in less waste, less emissions, cleaner water, and a healthier environment.

Complex adaptive systems, like circular economy value chains or industrial symbiosis clusters, can best be described with computational tools that enable the practitioners to see the consequences of context, relations, and input settings (Lange et al. 2021b). This also implies that for solid sustainability education, students can define what is needed for collective action and what can be done in an individual way. The sustainability of one production location, a factory, or a chemical plant, is most of the time impossible to define because of the embeddedness of that activity in a value chain or in an industrial park. The sustainability or circularity can then only be determined by a system perspective that takes into account several activities, a multitude of energy or material flows, and a diversity of stakeholders.

Both industry 4.0 and industry 5.0 need practice-oriented research in strong collaboration with companies and knowledge institutes (Schwab 2017). Industrial socio-economic modelling helps to focus our attention on the need for large-scale and rapid transformations in decarbonizing our industrial production and the critical need for renewable energy. The task in education programmes is to teach students about the complexities that are at stake here and to show them possible ways to increase system understanding also by scenario planning.

Scenario planning together with system analysis methods is fun to work with. It demands a lot in terms of creativity and personal involvement, but it also gives teachers and students a great opportunity to discuss what is important for individuals and societies. Sustainable development is not only indispensable for governments, education, or industry, it is also the only way to hand over our world to the next generations in a better shape than we found it.

Note

1 Highlights of Industry 5.0 by Frost and Sullivan, retrieved from https://www.frost.com/wp-content/uploads/2019/11/Exhibit_1.png.

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