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Chapter 9: Designing circular supply chains and eco-conscious infrastructure for sustainable manufacturing

9.1. Introduction

In order to obtain a sustainable form of living on Earth, it is absolutely necessary to achieve Nets Zero Production Waste in Manufacturing, defined as the waste managing and disposal to landfills, the release to Air or Water Pollution, the waste exporting or transferring to other nations, etc. This goal cannot be achieved only with cleaning and recycling technologies, because the cost of cleaning wastes and transforming them into something useful is equal or more than their energetic, financial, or ecological cost. The progress towards a Nets Zero Waste for Manufacturing is a true revolution in the way that products are produced for the economy and the society. This revolution has to bind very closely the efficient production of goods for the economy and the society to a rational elimination of Manufacturing Production Waste, which is something that mankind cannot abandon, as after a period of time the Waste Cost becomes an extremely expensive eco-economic cost. Neither costly recycling technologies or used waste dump zones or incinerators for reducing toxic or noxious gases are the economical answer. The only viable option to be endorsed is to consider the current actual form of manufacturing as being true and responsible for emissions and production waste and to be economically liable for the impact of the production process, until all forms of wastes are designed, utilized, and implemented directly in the form of Good Manufacturing Practice for sustainable manufacturing (Bocken et al., 2016; Geissdoerfer et al., 2017; Kirchherr et al., 2017).

This need reflects in binding the actual manufacturing to Circular Networks of Manufacturing Control Action Systems which are able to correlate the type, concentration, and quantities of the input factors utilized for producing goods to the type and degree of manufacture emission and production waste, being responsible for the eco-economic cost borne by society and the economy. Spanning all these aspects is the whole problem with manufacturing process realization, which is the theme developed in this chapter dedicated to Sustainable Manufacturing through Circular Supply Chains and

Eco-Conscious Infrastructure (Bocken et al., 2016; Despeisse et al., 2017; Geissdoerfer et al., 2017).

9.2. Understanding Circular Supply Chains

Conceptually, there is a circular economy where the value of both products and raw materials is maintained by reusing, refurbishing, remanufacturing, and recycling the product or its parts, respectively. This vision strives to avoid creating waste and to minimize the negative impacts. Accordingly, the role of production companies is much wider than just converting raw materials into products: There is a phased operation of design, manufacturing, and distribution followed by use and post-use activities including waste management such as disposal, recycling or remanufacturing. A circular supply chain enables a transition from a linear to a circular economy. Companies today are focusing on creating sustainable supply chains that satisfy the needs of customers while keeping the environment in mind. The circular supply chain concentrates on a shared goal of bringing everyone including consumers into making sustainable choices that require less energy by designing and packaging products according to the closed-loop approach.

Implementation challenges largely stem from the fact that the majority of supply chains resist any disruption to their traditional linear path, especially if there is no certification available that both validates the credibility of products and process adherence and ensures their quality. Companies investing into circular processes expect for external factors to motivate or compel the counterparts upstream and downstream from them to the same commitment, sharing the overall costs and risks. Hence, regulatory incentives, customer validation, and industry-level certification will pave the way for a number of pilot implementations which will accumulate enough evidence about the quality aspects of circular products to support private and corporate customers' willingness to pay higher prices, thus inducing a business case for the involved companies to further commit resources.

9.2.1. Definition and Principles

Circular supply chains (CSCs) offer an alternative to traditional linear models through which supplies move in an irreversible flow from extraction through production, distribution, and consumption to a waste state. CSCs recover the waste at their end point to drive a further circular flow of materials through the system, preventing their irreversible exit and creating virtual networks. These networks decrease pressure on environmental boundaries by ensuring that used products are recirculated correctly, hence partially offsetting resource depletion, land degradation, and pollution from landfilling and incineration. In this manner, CSCs offer an answer to the waste, energy, and security crises facing modern societies. Recognizing that today's disposal is for tomorrow's resource, CSCs rest on several principles. Chief among these is the interest to recover value embedded in disposed products and avoid the continued need for virgin resources to create new supplies. Products cannot be directly disassembled into materials for resale, hence a market has to be created to incentivize the disassembly of no-longer wanted goods, the labor and business cost of which will ultimately determine the value of the output. The existence of a second-hand market creates demand for both the energetically inexpensive refurbishment of categorical goods still in good condition and for remanufactured products.

Fig 9.1: Circular Supply Chain

The collaborative activities involved in the remaking and reuse of disposed consumer goods directly influence the market for secondary products while assuring the efficient supply of products (or materials) into recovery for factory purposes. Material recovery therefore encourages vigilance with regard to having the right product type in the correct geographical area at the right moment for the raw input requirements of receiving factories. These functions are realized through a set of CSC operations involving preparation, refurbishment, industrial resending, and transfer.

9.2.2. Benefits of Circular Supply Chains

Pamela L. Kafka establishes the connection between sustainability, eco-conscious infrastructure, and circular supply chains. The author highlights the need for a closed-loop, waste-free environment, abiding by principles that sustain economic prosperity, reduce depletion of resources, reduce waste, and maximize usage of available resources. The inherent traits of sustainability are guiding forces in planning for current and future generations to inhabit ecosystems while enjoying the benefits of a manufacturing economy and society. Eco-conscious infrastructure addresses sustainability within the built environment through a commitment to design and build infrastructure facilities and systems that minimize greenhouse gas emissions throughout the life cycle, support the economy with investment in needed public facilities and systems, address the priorities of community in a manner consistent with maximizing the benefits to society and future generations. Given the need for sustainability, why are not circular supply chains in predominant? Initiatives on sustainability continue to evolve, while companies struggle with the concept of additional costs associated with an effort to be environmentally suitable and successful in a competitive global market. Energy conservation costs money; tax credits and incentives cannot eliminate the associated costs. However, in the demand for acceptance in the marketplace, many consumers favor products considered "green". What are the benefits of having a closed-loop, circular supply chain? Although assessability for initiating a closed-loop, circular supply chain initiative is based on a company's involvement in industries that indicate lengths of life cycles for their products, some desirable attributes emerge. Through design modification, products can be designed for disassembly, repair, and reuse. As product recovery increases, greater amounts of materials are available for recycling, reuse, and remanufacturing, creating the opportunity to develop competitive advantages relying on product quality, price, and availability. By returning valuable materials back to the production process via recycling or remanufacturing activities, manufacturers reduce the demand for virgin material and processing waste, and considerable savings can accrue. Recycling utilizes energy low in comparison to that consumed in the manufacture. Marked corporate and brand identity accrue for integrating sustainability within the organization value chain as the organizational value goes beyond the shareholders to being stakeholder and market focused.

9.2.3. Challenges in Implementation

Although circular supply chains are conceptually simple, their realization is often fraught with practical difficulties, including: demand volatility and complexity, network design and configuration, product design integrity, technology needs, maintenance quality control, software and hardware integration, uncertainty in yields, scalability issues, transportation inefficiencies, disassembly knowledge and labor requirements, lack of commitment from partners across the chain, product contamination risks, legal implications, development and management costs, and implications on organizational competency and culture. Circular supply chains can be complicated by dizzying numbers of ever-changing mandates and government incentives, particularly in developing nations. In particular, manufacturers that depend on imports from countries downstream in the supply chain must take those countries' policies into account; changing a product to avoid tariffs may obviate planned circularity. Moreover, this latter challenge raises the visibility issue: packaging and labeling transparency can be a burden for both manufacturers and consumers. Because any alterations to a product may open manufacturers to litigation, predictive modeling and heavy oversight of all aspects of a supply chain is essential. Affected companies should be prepared for expensive rebranding efforts if laws change to require more disclosure; the high cost of such a revision may counteract the organizations' investments in environmental sustainability. The job of monitoring product-specific data is increasingly falling to software suppliers. They are developing solutions to enable circularity and disclosure as becoming less difficult to control and detect. These include reporting technologies, and software for digital twins that monitor materials throughout a product's entire life cycle.

9.3. Eco-Conscious Infrastructure

Infrastructure is considered eco-conscious when the selection of materials and manufacturing techniques, the energy spent during their fabrication or on their function, and the environmental impacts happening during their lifetime, including at the end-of-life, are all low enough to foster a sensible commitment towards sustainability. Materials and technologies used for infrastructure and product components have to be as low-impact as possible regarding their energy and material footprints, emissions, relative recyclability, and other important factors. Renewable energy powering manufacturing and functioning processes is also essential to cope with commitments regarding sustainability. Beyond that, energy and resource-efficient components with a long lifetime must be the favored solution. The long lifetime implies that the use of dangerous materials must be banned. Waste during and at the end-of-life of components has also to be incurred as little as possible. Finally, on the more global side, the contribution of infrastructures must be focused both on specific location and their holistic function - like water balance or health effects - and on a whole economic or ecological area. The fabrication of eco-conscious infrastructures requires a strong commitment not only from their manufacturers and policy decision-makers but also from product developers and manufacturers. They have to work on the optimization of energy and resource consumptions, the reduction of waste generation during component and infrastructure production and functioning, the recyclability and reuse of the different materials and components, the regeneration of ecosystem services - like water balance and sugar compensation during climate events. Ultimately, the development of closed-loop supply chains is critical, targeting loops where both component producers and infrastructure builders and operators are partners.

9.3.1. Sustainable Materials and Technologies

The negative effects of unsustainable mining practices are apparent around the globe. Developed countries typically have stricter regulations when it comes to mining and use advanced technologies to limit these impacts. However, most developing countries lack resources and regulatory frameworks to limit the damaging impacts of mining, often in search of economic gain. The long-term health and environmental impacts are devastating. Therefore, solutions that increase the reuse and recycling of mined primary raw materials, increase the utility and durability of primary raw materials, or substitute greater quantities of recycled raw materials or secondary raw material alternatives in manufacturing, construction, and design, will reduce pollutants and other externalities, while increasing returns generating economic activities and long-term gains.

New technologies play a major role in eco-conscious design. Virtual modeling and simulations will change how we design and assess the initial step of any process. Incorporating lifecycle thinking will make it possible for the architectural and structural industries to analyze competing designs based on resource extraction and energy use rather than shorting energies. 3D printing enables environmentally-compatible and local material use. Virtual and augmented realities will help visualize the effects of different design alternatives. Artificial and virtual intelligent decision-support systems promise to make it economically tempting to explore the use of other specialized material design tools at the market disposal.

Further development in industrial symbiosis, closing the loops, promotes profit sharing across companies by exchanging and using each other's leftover materials. They specifically promote partnerships between companies that create energy and waste. However, the support of design tools already mentioned, and advanced policies, laws, and finance regulations are needed to further develop these new technologies, in order to achieve a circular economy in our manufacturing ecosystem and economy and our societies as a whole.

9.3.2. Energy Efficiency in Manufacturing

More than 80% of world electricity is produced using fossil fuels, and world cement industry alone contributes 8% of global consumption. With the projected growth in electricity demand, it is conceivable that the heavy dependence on fossil fuel will continue, and global warming would be further accelerated. For a sustainable future, manufacturing processes should be transformed from fossil fuel energy consumption to a sustainable energy mix with renewables and nuclear as the major resources. The energy consumption for major manufacturing processes is depicted in a structure, the focus is almost completely on sustainable heating technologies for major heat energy manufacturing processes directly linked to fossil fuels consumption, and these efforts will to a large extent, can be transferred to other heat energy driven processes.

Renewables such as biomass, concentrated solar, geothermal, biofuel and hydrogen could be clean alternatives to replace fossil fuels for heat manufacturing applications, and could boost the energy intensity reduction in these applications substantially. Nuclear waste heat could also perhaps be considered in some specific applications. Some examples of these alternative heat technologies that are found feasible are; solar for glass melting, zinc and proofing and solar, biofuel and hydrogen for fossil-fuel free cement production. Electricity is also a major component in the industrial strategy by being the highest impacting method, especially in non-fuel manufacturing processes, in tackling global warming. The wide gap between emission and demand growth and generation level is being addressed by paradigm shifts, such as wind-turbine, photovoltaic, and other green innovative technologies being aggressively pursued in both research and commercialization, to make the electricity bulk mix carbon neutral by 2030.

9.3.3. Waste Reduction Strategies

While resource efficiency and energy efficiency are primary concerns to promote sustainable manufacturing, reducing the negative effects of production requires reducing the quantity of wastes produced. Two different strategies are commonly considered as a means of reducing waste in manufacturing activities: reducing interim and end-of-pipe wastes, and removing production processes that would cause a negative impact on surrounding communities. Obviously, the ideal goal of any sustainable production system is to choose technologies in such a way that it is not necessary to dispose of product by-products. However, in different situations, such as with product systems that are above the acceptance value for non-environmental SME, manufacturers may choose to dispose of SME caused in a project-based process, or provide cleaning during the entire manufacturing activity.

Technology innovation plays a key role in adopting waste reduction strategy. If, for example, the pharmaceutical and chemical industries use batch processes, it is necessary to clean cleanroom and service areas every time raw materials are manipulated. This service is costly in terms of time and workers, as well as negative impacts caused on communities in terms of high-energy consumption. Besides that, implementing or continuing to implement so-called "service cleaning" during production may not be enough to eliminate the risks of being in the courts of the regions affected by pollution. In this perspective, using continuous production technology can eliminate the "need" for so-called service cleaning. Such technology has been applied in the photolithography sector, where special coatings are used on the surface of lamps emitting various lengths of light waves; continuous production of energy, for example, by using gas turbines; and photobioreactors for microalgal cultivation, which can extract energy from organic matter created by biophotodesign of an entire microalgal production system.

9.4. Key Components of Sustainable Manufacturing

Sustainable manufacturing includes a number of key components and design systems. Life cycle assessment (LCA) is a tool that can assess a product's environmental impacts across its life cycle and identify problem areas with excessive consumption of resources or emissions. A number of software programs exist that can assist with LCA of a product. Also covered are parameters for an ecological-based foundation that directs the selection of green approaches for developing sustainable products and the integration of selection parameters into existing design systems. Attention is also given to recovery techniques that deal with the reprocessing of end-of-life products. Products should be designed to either facilitate recovery after their useful life or to be remade using a minimum intra-generational and inter-generational resource and energy commitment to restore the reclaimed resources in order to create sustainable societies.

Life cycle assessment (LCA) identifies and quantifies the input and output flows of materials and energy from their extraction through product manufacture, use, disposal, and potential recycling. LCA allows designers as well as consumers to evaluate the environmental consequences of decision-making and make choices that lessen negative long-term impacts. LCA makes it possible to quantify data to tackle the growing concern about depletion of resources, pollution, and health danger hazards that are often associated with manufacturing. This ability may in turn influence policy development within manufacturing as well as governmental and regulatory agencies. These assessments can then be included within the product databases. Product LCA impacts can also be coupled with analytical and judgment basis to determine the most significant areas and/or manufacturing conditions at a particular phase.

9.4.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is an analytical tool in which all the inputs to and outputs from a functional system are determined and examined. Assessing systems at both global and local scales provides insights into resource demand, material flow, pollutant emissions, and associated impacts. Quantifying the impacts throughout the life span or life cycle of a product is a meaningful way to assess how that product compares to the other products. A growing number of products are being evaluated using LCA methods based on policy, market, and strategy driver requirements. Several standards are connected with LCA.

The functional unit is the basic unit to which inputs, outputs, and internal exchanges are related. The functional unit's purpose is to establish and define the service provided by the study's subject, or functional system, to enable comparisons between products. The functional unit is typically concrete, but may also be an abstract component; this does not issue severely on the comparability of products provided that the various assumptions are made clear. For example, measuring the embodied primary energy of a window as compared to a building with a defined life span and design serviceability may or may not be a valid basis for comparability. The design unit for comparing different product designs or different corporate product portfolios could also be physical, but there is little experience with this approach. Whether the existence of comparable physical design units or design services would facilitate or complicate cross-design or cross-business comparisons remains to be shown. Hence, the main process is to develop a functional comparison bilateral to a physical design parameter comparison.

9.4.2. Sustainable Design Principles

In addition to performing life cycle assessment on invented products, it is imperative to utilize design principles for sustainable manufacturing that are rooted in nature to produce products that have minimal negative effects on and ideally positive contributions to society and the environment. In the sub-sections that follow, we provide a summary of some common sustainable design principles and their relationship to various assessments. The intention here is not to provide an exhaustive list or explanation of these guidelines. We hope that they will empower the reader with normative guidance as well as explicit design language and taxonomies to facilitate the sustainable design process and the conceptual design of more environmentally friendly products.

The emphasis of this section is to furnish students and practitioners related to product design with explicit design criteria to ensure that the product designs are sustainable. There is a plethora of resources related to sustainable design guides, principles and methodologies. Sustainable design involves the development of products that are not harmful to the environment. However, the fact that such a definition is not adequate in terms of the life cycle of the product has led to new concepts with a broader approach, which is known as life cycle design, in a return to the roots of the sustainable concept but taking into account the totality of the product life cycle. Such schemes already exist in the form of criteria, principles and checklists that orient the design. However, they are not enough to help the designers, mainly because of their vague sense and lack of specificity. The deep and multidisciplinary design task requires considerable information, but often the designer does not have it. The design-related information to consider in order to meet these criteria is associated with a design domain.

9.4.3. Resource Recovery Techniques

Remarkable resource recovery techniques, such as remanufacturing, reuse, recycling, energy recovery, composting, and incineration can help in resource exhume and depletion aspects of Sustainable Manufacturing. The circular supply chain concept can also be applied to resource recovery as outflow and inflow of resources play a crucial role in both cases. For example, finite reserves of the earth's surface layer are used to produce new products while a supply chain handles the product to the customer. When sufficient value is no longer perceived in the product, it enters the resource recovery chain, which using various resource recovery techniques attempts to restore its value. If successful the valuable resources replenish the supply chain for new product development. Resource recovery techniques represent a number of options that have been developed to reclaim materials and energy from waste at different levels within the hierarchy of options available. The concentration at the top of the pyramid indicates the most desirable and valuable resource recovery options with the least cost. These techniques allow energy and materials to be reclaimed and reprocessed, thereby recovering substantial economic value from spent products at the end-of-life as well as reducing potentially negative environmental or social impacts associated with the waste. Within the above resource recovery hierarchy below are shown several techniques, which may be applied for a variety of resource recovery options relating to different resource types and categories. Process efficiencies can be increased through further development of existing techniques and more importantly development of emerging technologies that advance the state of the art.

9.5. Case Studies of Successful Circular Supply Chains

Over the years there have been industry examples of supply chains, which are built on circular principles. Not only do these examples exist, but also lessons gleaned from their success can help the future engineer the adoption of new circular supply chains.

The Dutch company, Philips, is a well-known household brand name associated with the manufacture of small as well as large electrical appliances. Fewer people are aware that Philips has developed an expertise around product stewardship and the collection of products at their end-of-life in order to recycle product input materials into new products. The company not only collects its own products for recycling but also performs this service for third-party customers as well. The system is not unlike the approach taken with used batteries; make it easy and convenient for customers and they will use the service. Philips provides a means to collect used electronic equipment for recycling in-store at their sales outlets around the world. Philips also operates collection and recycling centers in various locations. This has allowed the company to recover new input materials from old electronic equipment not only at their own facility but also from third-party business locations.

The reuse of products many times over and the recovery of product input materials at their end-of-life needs to be engineered into the product design and development process. Decisions made at the beginning of the supply chain design journey will impact the ability to achieve reuse and recycling in a positive sense or a negative sense, later in the product's life. There are organizations created to help businesses and government work together to reduce waste, develop sustainable products, and promote the circular economy. They have created a set of product design principles, which advocates should be followed to help ensure that a product not only remains in use as long as possible but also recovers value at its end-of-life.

9.5.1. Industry Examples

As an important measure to global concerns about climate change and sustainability, industry plays a major role in the pollution emissions, contaminated waste production, but also in the solution to offset resource extractions and the provision of corrective investment. As an important activity within the industry, construction and the provision of ancillary products and services, such as manufacturing and maintenance are increasingly heavily weighted in terms of socio-economic contributions but also in terms of ecological footprints and environmental load. In consideration of the prospective anticipated increase in these activities, tailor-made approaches to the efficient reduction of the indicated negative consequences must be developed and implemented with urgency. Strategies such as those stemming from the circular bioeconomy, circular economy, and industrial ecology have already shown promising concepts and partial solutions. Further contributions to an overall circular strategy can be provided by a circular supply chain management in close connection to an eco-design and henceforth development of a respective eco-conscious infrastructure.

Current efforts, however, are still rather shy in volume, variety, depth, and genius, and in need of further design and enhancement to generate the effort in order to be able to tackle the indicated challenges effectively. These contributions herein are to serve as a seed for more intricate subsequent designs for a truly clever and sustainable circular strategy. A first widely cited industry example is that of a multinational organization's pioneering approach to a closed-loop carpet supply chain, showing the potential of travelling the way from a linear to a circular supply chain model and the environmental as well as competitiveness advantages stemming from doing so. In reducing metal resources, the initiatives pursued in the beverage can industry have similarly set a benchmark for sustainability in circular schemes, contributing to the early days of the development and proliferation of circular economy concepts.

9.5.2. Lessons Learned

The involvement of stakeholders from product design through supply chain planning, utilization, and eventual end-of-life policies is instrumental. At a minimum, product design should involve stakeholders in the supply chain whose service and spare parts impacts drive the majority of support chain flow. Such stakeholders could include supply chain partners involved with repair, refurbishment, remanufacture, restocking, and recycling of product and byproduct flows. Moreover, the product design phase needs to visually simulate the possibilities for reuse, repair, reclamation, refurbishing, resale, remanufacturing, and recycling. A collaborative approach at the earliest moments of the planning horizon will certainly enhance supply chain relationships and supplier expertise over time and thereby drive greater visibility. The burgeoning use of digital twins may greatly enhance such group decision-making opportunities by extending many product life cycle design aspects. The design model must also accurately capture the transition between states; from core state of storage, it can move from services in Progress/Work in Process, disposal cost, Customers installed/Customer product usage, Support parts flow, and product Restore/Restoration to serviceable condition/Quality; and from the byproducts' Reprocess/Recycling to the stage of Resource material.

Whatever mix of policies emerge from the partnerships of supply chain organizations, collaboration and strength of relationships to ensure mutual benefits of all partners will certainly enhance the success of closed-loop supply chain management. The need to incorporate the downstream product and technology system users and the channel of selling and servicing products and systems is critical to the emergence of effective closed-loop supply chain management. In fact, the signal of this demand need may be incorporated into a digital twin experience or artificially driven into the design efforts.

9.6. Regulatory Frameworks and Standards

A dearth of regulation and standardization has hampered the swift upscaling and adapting of the circular economy for infrastructure and manufacturing. Despite dedicated government initiatives to support the establishment of product and infrastructure recycling and upcycling, regulations and standards for circular infrastructure design remain rudimentary. Various aspects of sustainable design, eco-design, recyclability, and substance bans are covered by specific environmental product declarations. However, specific guidelines for circular plastics, substrate, or metals are missing. Only the most established and mature standards for aluminum offer circular guidelines beyond simple circularity keys.

The European Union recognized the urgency of standardizing circular economy pathways and definitions and commissioned a work program for the development of overarching specific norms. Mirror groups have been founded to oversee the task and ensure industrial applicability. The growing advocacy for circularity across industries has led to industry works from several European commissions, paving the way for swift practical circularity uptake. These independent industry coalitions that incorporate diverse stakeholder groups have pioneered circular economy-specific norms for concrete, steel, timber, water, and plastics, along with asset and product circular requirements across materials and life cycles. The planned establishment of these industry standards as regulations will most vigorously bolster the shift towards the adoption of circularity-for-profit pathways and asset reuse, with more funding options becoming available to back up the necessary digital interlinking updates. Supported by the availability of regulations, the incorporation of circularity into available methods, tools, skills, and timelines is straightforward.

9.6.1. Global Regulations

Global and domestic public policies are one of the main drivers for circularity at the supply chain and life cycle stage. There are also many private regulations that support these efforts. Here we focus on giving an overview of public regulations. There are a lot of international, multilateral, and supranational treaties and initiatives that support the circularization of supply chains and infrastructures. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal supports the environmentally sound management of hazardous wastes. The Rotterdam Convention runs on a similar premise for certain hazardous chemicals and pesticides, associated with the transboundary trade of such products. The Stockholm Convention on Persistent Organic Pollutants owns additional commitments with regards to the exporting parties. These huge logistical flow of hazardous materials must be supported by eco-conscious infrastructures. The Montreal Protocol on Substances that Deplete the

Ozone Layer, the Convention on Long-Range Transboundary Air Pollution, or the United Nations Framework Convention on Climate Change are more aligned with the eco-consciousness of the infrastructures. These international initiatives link sustainability challenges to international law. These texts can be the basis for imposing stringent requirements for circular and eco-conscious infrastructures.

Fig 9.2: AI-Driven Circular Economy of Enhancing Sustainability

The Kyoto Protocol on Climate Change adopted the Clean Development Mechanism to create incentives for developed countries to invest more in less developed countries and therefore create supply chain flows working on more strict emissions standards. The trade of carbon emissions credits exists mainly with companies from developed countries with reduced emissions and investment in less developed countries with outdated production processes using cheap labor, with high emissions. The international carbon market can play a reinforcing role in the development of eco-conscious infrastructures and sustainable supply chains. As mentioned earlier, the EU Green Deal is entering into various regulations that will impose incentives or barriers for circular supply chains. One of them is the EU Trade Policy Review. This review makes an evaluation of the free trade agreements signed by the Union with surrounding countries.

9.6.2. Local Initiatives

Many of the initiatives being developed have a local nature. For example, in Spain, the Integrated Urban Waste Management Plan of the City of Madrid seeks to support job creation in the recycling sector, increasing the recycling rate of the municipal waste generated to 25% and recovering 10% of the municipal waste generated with compliance with the regulations that guarantee quality and safety in the manufacturing processes. In Italy, the Regional Waste Management and the National Strategy for Sustainable Development proposed the creation of networks to facilitate the realization of eco-industrial parks. A similar initiative existed in Tasmania, where the development of EIPs was promoted through the Tasmanian Industry Council, the joint agency for promotion and development of Tasmanian industry. EIPs were created to promote resource efficiency by recycling the outputs of one area to be used as inputs by another area. Arguably, EIPs on a small scale would have a greater effect than EIPs on a larger scale. A proposed development of a small-scale EIP aimed to support a local area of Sicily. A prominent project is the C.I.S.E. which is not part of any policy. C.I.S.E is based on the principles of circular economics, focusing on sustainable development strategies and local development with zero waste policy. C.I.S.E. aims to address the problems of localized marginalization and socio-economic erosion through the generation of new and quality jobs, aimed at improving local living conditions and safeguarding local ecosystem functionality, also through the support of participatory processes among operators and citizens.

9.7. Technological Innovations in Circular Manufacturing

The development and deployment of advanced technologies in manufacturing has made production more efficient at scale, but left giant gaps in equity and sustainability across supply chains. Flexible robotic automation, artificial intelligence, and additive manufacturing have the capacity to reshape the economic calculation of going circular by bringing the activity closer to the point of consumption, and in doing so, minimizing the footprint of production, while maximizing reverse flows of used technologies back to primary producers and their suppliers. Enabling data driven decision-making, transparency, and stakeholder engagement across product lifecycles are emerging capabilities that technology can provide that increase the effectiveness of going circular, by ensuring that the necessary markets for the products and their inputs exist. Key underlying technologies that are key ingredients of this capability uplift are discussed next: digital twins combined with IoT, blockchain, and artificial intelligence.

Digital twins can be considered the advanced cousin of products with embedded IoT devices, but where the original developers make an additional investment in creating a detailed information profile of the product or service, which allows it to persist as a digital entity for the full lifecycle of the product or service. Such digital twins can then act as the fully-functional, lightweight lifelog of the product or service during its lifecycle, with graphics already representing the current configuration and analytics operating on them. Data from the IoT can be utilized to rapidly update both the logic and graphics of the digital twin, allowing stakeholders to see a lifelike representation of the present state, and changes to the functionality of the product discussed. The lifefulness description of a digital twin can use qualia as identifying and storytelling features that are likely to arouse a greater investment of attention and hence be more memorable to the stakeholders.

9.7.1. Digital Twins and IoT

Industry 4.0 technologies and applications present exciting opportunities to more fully implement the ideals of circular manufacturing. Advances in cyber-physical systems, IoT, big data, and cloud computing enable the flow of real-time data up and down the supply chain. This allows manufacturers to have greater visibility into the changing conditions of the internal and external environments, identify new and emerging constraints, more quickly respond to changes as they are occurring, and dynamically re-optimize and reschedule operations and the configuration of supply chains. These technologies provide more complete feedback loops to enable circular systems, such as allowing real-time tracking of product condition to enable take-back for repairs, remanufacturing, and recycling at the end of product life. Real-time tracking of products, materials, and their condition allows supply chain partners to dynamically share and update information about flow, enabling near real-time coordination of dynamic changes in supply and demand. IoT, in conjunction with digital twins, is well suited for modeling a rapidly changing and dynamic industry that requires real-time response to quickly changing disruptions while operating under new challenges for risk, resiliency, and sustainability. The near real-time visibility enables the management of volatile production schedules while also ensuring adherence to requirements for sustainability and circularity. Digital twins will be further enhanced in the future to allow the incorporation of environmental effects models that give better insight into the sustainability characteristics of the current configuration of the manufacturing system.

9.7.2. Blockchain for Transparency

In recent years, blockchain systems have become a highly popular mechanism for providing a fully decentralized, global system for ensuring both verifiability and integrity in a wide range of applications. In essence, a blockchain provides a way to store and verify evidence of events within a system, and it provides a mechanism by which that evidence can be verified and nullified while providing a guaranteed, identifiable, and unattackable point of reference. This information can be either information that inherently has value or may only be a specific identifier, timestamp, and evidence to prove that a specific event occurred that influences value in another system. These capabilities make blockchain potentially powerful for providing not only auditing capabilities but also tracking properties of components flowing through the supply chain in a manner that enables the principles of circular economy.

Unfortunately, several problems still need to be solved before blockchain can realize its great potential. For example, the cost of entry into a blockchain can be very high in large transactions due to the energy inefficiencies, including cryptocurrency demand and costs. Another issue is the interoperability of blockchain strategies. Each enterprise typically invests in a private, internal, enterprise-level blockchain model that will not connect to the external enterprise blockchain models of its suppliers, suppliers' suppliers, clients, etc. This means that the only verification possible of a private blockchain occurs internally, and the validations of components by trading partners still require independent and costly third-party verifications. Perhaps the greatest remaining issue is the security of the models. While crypto strategies perform adequately in terms of security resources, many firms are concerned about allowing outside firms to verify their internal data flows without necessarily allowing those outside partners access to their other operating data.

9.8. Stakeholder Engagement and Collaboration

Sustainable Manufacturing (SM) requires stakeholder engagement and collaboration across the supply chain. A sustainable supply chain design process requires a minimum of two interrelated prerequisites to be effective in achieving the sustainability goals of the firm and making the right supply chain decisions. The first prerequisite is the stakeholder engagement process that provides information about sustainability criteria about the supply chain design options that are relevant to the stakeholders and requires sustainable supply chain design decisions that impact stakeholders’ value systems. The second prerequisite is the need for a sustainable supply chain design decision support tool that provides information supporting the stakeholder collective choice of the sustainable supply chain design decisions. Collaboration with stakeholders also implies governance processes and structures to support resource flows and transaction modalities that enable the allocation of risks and costs among stakeholders. The concept of stakeholder capitalism that emerged from multiple stakeholder dialogues generally advocates the public disclosing of climate-related metrics across stakeholder groups.

While both the product design process and the sustainable manufacturing process are designed around meeting consumer needs, the consumer is rarely consulted about either process, particularly the sustainable product design process. The emphasis has usually been on offering incentives and nudges based on consumer value systems for their expression in product selection, not consultations. We believe that consumer engagement in the above processes is critical to the achievement of net climate impact goals. This engagement creates the pathway for consumer acceptance and minimizes the investment risks in sustainable product design and sustainable product design decisions and lifecycle assessment coefficients that guide decision support tools for sustainable product standards by businesses.

Sustainable products for consumers require holistic sustainable design approaches that account for all impacted stakeholders and their dependencies in the design process. These products are produced in sustainable manufacturing systems across a sustainable product value chain. However, the processes of product design development, selection, and manufacturing are seldom integrated and simultaneous. Addressing these weaknesses requires consumer engagement in the lifecycle product development, collaboration across the supply chain stakeholders involved in product manufacturing, and the involved considerations of each stakeholder’s technology and investment capability in product design and manufacturing.

9.8.1. Role of Businesses

Interest in sustainable business practices is growing rapidly. A major contributing factor to this increasing interest is the expectation that business organizations take responsibility for minimizing the ecological impacts resulting from their activities, as global citizenry acknowledges that business has the resources to effectively tackle many of the challenges facing the earth, such as climate change, water scarcity, environmental pollution, and biodiversity loss. Researchers, as well as practitioners and policy makers, have begun to explore the role of businesses in pursuing sustainable development. CSR is described as a concept that helps companies to integrate social and environmental concerns into their business operations and stakeholder interactions. CSR is “the responsibility of enterprises for their impacts on society”, and “to fully meet their social responsibility, enterprises should have in place a process to integrate social, environmental, ethical, human rights and consumer concerns into their business operations and core strategy in close collaboration with their stakeholders”.

Successful businesses do not exist in isolation in a well-functioning market for their products and services. They work with their employees, suppliers, and customers, and they are part of the local community. The organizations expressing a commitment to CSR have identified public concern and stakeholder expectations in relation to environmental matters, supply chain management, and global poverty alleviation, and have undertaken responsibility to better manage those issues through core business practices. This increased level of collaboration and interconnectedness has also been facilitated by the increased reporting disclosure requirements of sustainable practices through legislative and regulatory action encouraging or requiring the reporting of CSR goals and achievements, sustainability reports, and other environmental performance information by businesses.

9.8.2. Engaging Consumers

Over the past few decades, environmental issues have captured the public's attention like never before, as evidenced by staggering documentaries and extensive media coverage of melting ice caps, the Pacific garbage patch, dwindling natural resources, and persistent pollution. City and building designs often don't follow these trends and sometimes create physical barriers that segregate the public from green initiatives. Just as we see connection in almost all new smartphones, the circular economy is an inherent goal of every new hub, maker space, and destination, either consciously or subconsciously. However, while some consumers are excited to see sustainability incorporated into products, they may also be skeptical. Concerns include companies overstepping or acting in bad faith, and doubts that supply chain practices can ever be as green as advertised. Businesses need to support consumers to help them feel that they are being included in the circular economy, or else they may think it is yet another feigned attempt to sell green products that will never deliver.

Few resources exist to help explain the complexities of a circular supply chain to consumers. Each party's motivating interest needs to be carefully translated from technolingo for consumers. One tool that can help in providing a direct view of supply chain activities for specific purchases, but companies need to ensure that consumers understand how to effectively use that data for their purchase and disposal decisions. Businesses also need to provide the right materials, at the right time, and in their preferred disposal manner. Research has shown that consumers care about the end-of-life of products; at the disposal stage, only 38% of consumers actually recycle sneakers or shoes, even though there are many recycling programs available, and 47% of consumers have never disposed of a pair of shoes or sneakers using the brand's mail-back program.

9.8.3. Partnerships and Alliances

Partnerships with stakeholders to ramp up adoption of circular benefits are critical, and can take many forms. Learning partnerships can arise, for example, in the strategies collaborative industrial systems operate on which the circular economy is based, such as eco-innovation networks, new business models, and establishing industrial symbiosis. A combination of public and private partnerships is often needed to increase resource and energy efficiency while enhancing economic development and environmental quality. Input and feedback from civil society is critical for the successful sustainability transition needed to make circular benefits contribute to explicit sustainability goals via transition to eco-conscious infrastructure and any industrial cycles connected to it. Research and innovation partnerships are also needed to allow scalable, active waste management, provide sustainable alternatives for food and feed, and to secure supply of renewable materials for markets and vulcanization produce positive global impacts according to sustainable development goals in each region.

Collaborative eco-systems involve sharing resources and capabilities among stakeholders available in eco-systems of local, district wide, sectoral, and multi-sector collaborative industrial systems. They can take the form of joint research services, joint R&D projects, information sharing arrangements, technology licensing publication sharing, training, consultancy, or bringing together different interests to identify and transfer environmental technology developments. From an economic perspective, this type of cooperation can be driven by the reduction of investment risk and implementation costs through the sharing of R&D and investment expenses. Directly or indirectly, this collaboration can obviate the need for national measures that otherwise would impose barriers or responsibilities on businesses, and create a competitive disadvantage and create higher costs for society as a whole.

9.9. Measuring Success in Circular Supply Chains

It is important to understand, however, what success looks like in a circular supply chain. Utilizing a circular supply chain strategy may be a way to mitigate risk and potential loss for traditional supply chains, but it is not a guarantee for an increase in profit in your bottom line. Although the primary intention for companies who engage in sustainable practices is to reduce negative impacts on society and the environment, it is a common misconception that it has to come at the expense of company profit. However, creating a circular supply chain strategy can yield a profit gain at the same time focus on the triple bottom line concept of planet, people, and profit.

Businesses should identify key performance indicators that are attached to their circular vision and strategy. Key performance indicators linked to long-term goals ensure that short-term operations will direct the organization towards their vision. Data management tools can track relevant data and include dashboards that highlight ongoing projects or quantify costs and savings, often in real-time. Utilizing key performance indicator tools can create company units, locations, regions, officers, or tracking categories. By filtering according to these criteria, it is possible to report and visualize data according to any specific organizational structure, enabling accountability, meeting required reporting specifications, and clearly demarcating responsibility. Demarcating reports within units of responsibility enhances accountability, enabling businesses to assure that each part of their company is reporting and addressing sustainability issues to mitigate risk.

9.9.1. Key Performance Indicators (KPIs)

As demand for C2C supply networks and industrial ecology networks rises, it becomes vital to monitor the performance of these new systems and their complex interrelationships, particularly to ensure that they truly contribute to sustainability. In this chapter, some illustrative suggestions are provided on how best to measure sustainability performance in a C2C environment. The aim of this chapter is not to prescribe a universal set of metrics, but rather to point to the ongoing efforts of many stakeholders who are developing specific, targeted methods. Specificity is crucial even at the most general level of qualitative or quantitative indicators, as any metric will intrinsically be organization- and context-specific.

The monitoring and assessment of C2C supply networks must take into account economic, ecological, and social development in the supply chain and geographically. In particular, the development of the efficacy of C2C-designed products and businesses would ideally show that: the useful length of the product lifecycles is increased; toxicological impact over the lifecycles is decreased; use of non-renewable scarce resources is decreased; resource consumption intensity over its lifecycle is decreased; virgin material input is decreased; resource productiveness is increased; and labour conditions, data protection, and social equity are improved. More generally, the industrial ecology and Vulcanization of the global economy is reflected by: impact leveling; resource peak shifting; benefits and capability building; efficiency and doing less bad of both business and ecological systems increased; and product/service value concentration. There is ample room for development of systems for monitoring progress towards these objectives. Such systems will differ according to the sectoral or geographic specificity and the evolution of the different dimensions of sustainability. Information technology will undoubtedly play a key role in such developments.

9.9.2. Reporting and Accountability

We suggest that two important documents are produced with our proposal, which relate to its reporting and accountability. First, a contents description of the intelligent life cycle, which publishes its contents on all units of the circular supply chain, and relates intelligent objects to intelligent factories where accounting documents are stored and verified using the intelligent life cycle and technology. This report is supposed to be a public report, which can be consulted in the interest of interested stakeholders. It is a much more informed approach to the topic of transparency, which nowadays uses the term “transparency” to justify issuing as little information as possible to outsiders. The second report is an accounting report, in which an external accountant verifies the work of the intelligent life cycle of all the supply chain’s intelligent objects. This transparency is thus well-defined, and not used as a cover for lack of transparency, as is often the case in many discussions on the subject. It must be noted that the traditional investment of external accountants is limited to the company where he/she has been chosen. For periods after the periods of initial establishment, the fact that the philosopher is so subordinate to the system of internal or within firm generative mechanisms may explain that such external check, imposed by the law, is voluntary, and concerns companies externalized outsourcing of significant parts of their activities, concerned with the aspect of cost control generation process with regard to financial constraints and margin considerations.

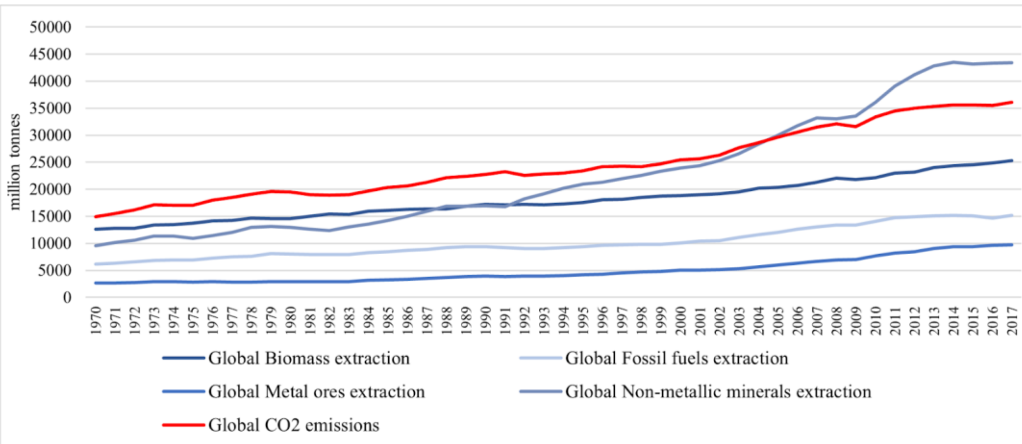

Fig : The Circular Economy as a New Production Paradigm

In terms of strategic objective measures we have made a sweeping statement: the companies and people who create a niche in the Circular economy will be the successful ones. In terms of how such a document could help, there seems to be agreement that it is a matter of how far away we are from the whole and its life cycle, the quality and quantity of variables describing its evolution vis-a-vis our observations, and the reputation of the speakers whose opinions we will weigh positively or negatively so that they evolve. What we are submitting to you is thus intended to help. However, while for other initiatives, the only accountability document is itself in terms of how much it exposes into measuring itself, we submit and suggest two additional documents desire to further this etymological pointing towards the desire to expose unto oneself, because we fear that neither of the two in its present continuously being criticized formats seems to be desirable by the speakers on all sides.

9.10. Future Trends in Sustainable Manufacturing

9.10.1. Emerging Technologies Many technologies in development today will alter the landscape for sustainable manufacturing over the next decades. These include nanotechnologies for energy storage and conversion that can lower greenhouse gas emissions or adapt to climate change; new biotechnologies for cleaning up contaminated lands, optimizing the supply of food, and creating biorenewable materials for production; new generation materials such as bioinspired minerals and systems to build energy-positive buildings; new fabrication technologies using natural and durable materials that embrace a circular economy during the product life and beyond; and digital technologies for advanced manufacturing, often termed Industry 4.0 and closer to the concepts of apprentice-making, responsible mass customization, and sustainable servitization.

Each of these technologies is either in a relatively early stage or being rapidly repurposed for a variety of products and new manufacturing processes. The challenges are both technical and social. Whether any of these technologies will support sustainable manufacturing at scale or in the long term is uncertain. The potential exists, but risks abound. Technology advances and spin-offs may not favor the early adopters and may exacerbate inequalities at local and regional scales. Digital technologies may widen the technology gap between developed and developing countries. Renewable energy technologies favor the rich more than the poor, at least initially: solar panels are more affordable if you live in a house with a roof, and electric vehicles in a garage for owners of more than one car. Bioengineered food may be more available in specialty shops or menu items catering to affluent consumers. Best practices need to be put in place to ensure inclusiveness in the design, development, and use of innovative technologies. Sustainable manufacturing is about local and global equity: the balance of adaptation, adoption, and installation.

9.10.1. Emerging Technologies

Sustainability is a goal that all parts of the world are aiming towards. Emerging technologies are changing the game in sustainable manufacturing and are therefore worth discussing. The emergence of Blockchain, Internet of Things, Augmented and Virtual Reality, 5G, Drones, Big Data, Clean Energy, Biodegradable materials, 3D printing, and Cybersecurity are discussed here.

Blockchain has emerged as a solution to intermediary problems and is perhaps the best tool to provide transparency in the manufacturing process. During the pandemic, the whole world saw the benefits of the vehicle manufacturing industry being able to shift to production of equipment used in hospitals, such as respirators. The argument that any manufacturing operation cannot pivot instantly is no longer valid. Blockchain, however, takes care of the reason that most industries give, which is the lack of transparency in the supply chain and the ability to find out whom they are receiving goods from, and that network being certified to be clean. Properly defining how Blockchain can interlink the ecosystem of manufacturing is where solutions lie. Incorporating IoT is yet another adjustment to the manufacturing process that can be incorporated into the ecosystem and need not be limited to just Blockchain. The amalgamation of both these technologies can help create eco-superstructures.

Augmented and Virtual Reality are seeing vast developments in application in training for safety and security in factories and manufacturing processes. 3D printing technology is such that increased application of it is going to keep getting cleaner as the printers move on to other clean sources of energy. Adopting print on demand technologies is going to become imperative in the future.

9.10.2. Market Predictions

The product segments that present the maximum growth opportunities for the sustainable manufacturing market are industrial machinery and precision instruments. In terms of geography, the sustainable manufacturing market is classified into North America, Europe, Asia-Pacific, Latin America, and Middle East & Africa. North America is expected to be the largest regional market by 2030, but Asia Pacific and Latin America may present more attractive growth opportunities. Investments in green projects to reduce the carbon footprint and a large consumer base that is increasingly conscious about social and environmental issues are predicted to be the major factors supporting growth in these markets. The USA is the largest market in North America. The major factors boosting the sustainable manufacturing market in the USA include the growing need to reduce flexible manufacturing costs, increasing users’ environmental awareness, and strict regulations imposed by the government on manufacturers.

In 2019, Europe held a 23% share of the sustainable manufacturing market in terms of revenue, and it is expected to witness a healthy growth in the next few years. The favorable policies and initiatives of various governments and the introduction of different standards are boosting the demand for fresh and renewable energy resources in the energy and power segment across this region. Manufacturing firms in countries such as Germany, France, and the UK are moving toward reducing their production costs and eventually increasing their overall profit by adopting sustainable manufacturing. The manufacturing sector in the Asia Pacific is the largest in the world by output value, supported by countries such as China, India, and Japan. The growing manufacturing capabilities of these countries are attracting industries from across the world. Furthermore, a large consumer base present in the Asia Pacific region has aroused the interest of companies.

9.11. Conclusion

By effectively managing supply chains, unsustainable manufacturing can be transformed into sustainable practices. For fulfilling this purpose, a new circular material flow concept has to be introduced, considering closed material loops with planning and controlling service-based product life cycles. For meeting these new material flow requirements and implementing industrial material flow infrastructures enabling the transition to sustainability, the tasks of infrastructure planning, modeling, simulation, management, and control need to be concurrent. The challenge is to derive generic modeling and design tools, including information, planning, designing, and simulation of modeling tools using multi-agent or complex network system principles, methods, and theories, for describing the new circular industrial infrastructures and to translate this generic competence into concrete infrastructure systems' models and tool applications that provide the engineers of produced infrastructure systems with the required qualities. Emerging technologies providing both modularization-based flexible production infrastructure components and tools to plan service-oriented product life cycles put the basis to achieve the merging and integration of product system and industrial infrastructure system design to be successful.

Due to the complexity of such industrial infrastructures and groundbreaking technologies for autonomous sensor networks, artificial intelligence, robotics, or digital twins, advanced tools like avatar modeling and simulation are required to develop a new research roadmap that conquers these upcoming challenges. To strongly facilitate the explicit consideration of resource sustainment issues in product life cycle planning and to support the related engineering need for new evaluation and modeling approaches based on different kinds of models. There is huge research effort behind supply-oriented product family planning models. The inevitable consequence of the increasing globalization of product spaces and of product life cycle engineering processes is the necessity of physical resource infrastructures to deploy and maintain manufacturing capabilities in a sustainable way.

References

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221–232.https://doi.org/10.1016/j.resconrec.2017.09.005

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308–320.
https://doi.org/10.1080/21681015.2016.1172124

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., ... & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. Technological Forecasting and Social Change, 115, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021