JOHNSON MATTHEY
TECHNOLOGY REVIEW

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Intelligent Resource Use to Deliver Waste Valorisation and Process Resilience in Manufacturing Environments

Moving towards sustainable process manufacturing

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Circular economy (CE) thinking has emerged as a route to sustainable manufacture, with related cradle-to-cradle implications requiring implementation from the design stage. The challenge lies in moving manufacturing environments away from the traditional linear economy paradigm, where materials, energy and water have often been designed to move out of the system and into receivership of waste management bodies after use. Recent applications of industrial digital technologies (IDTs: for example internet of things, data-driven modelling, cyber-physical systems, cloud manufacturing, cognitive computing) to manufacturing may be instrumental in transforming manufacturing from linear to circular. However, although IDTs and CE have been the focus of intensive research, there is currently limited research exploring the relationship between IDTs and the CE and how the former may drive the implementation of CE. This article aims to close the knowledge gap by exploring how an IDT (data-driven modelling) may facilitate and advance CE principles within process manufacturing systems, specifically waste valorisation and process resilience. These applications are then demonstrated through two real-world manufacturing case studies: (a) minimising resource consumption of industrial cleaning processes and (b) transforming wastewater treatment plants (WWTPs) into manufacturing centres.

Introduction

Manufacturing drives the economies of all countries from low to high incomes; contributing 16% to global gross domestic product and 23% of global employment in 2017 (1). Manufacturing is split into two branches: discrete manufacturing (automobiles, computers and electronics, textiles) and process manufacturing (chemicals, food and drink, pharmaceutical, fast-moving consumer goods (FMCG)). The difference is that discrete manufacturing is the cutting and assembly of a bill of materials into a final distinct product (2), whereas process manufacturing is the thermal, chemical or biochemical conversion of resources into products, byproducts and waste streams (3). Both share the core value that their products and processes must be profitable to remain in business (4). However, there is mounting pressure for businesses to become not just economically sustainable but also environmentally sustainable.

A key goal of sustainable manufacturing is to conserve energy and natural resources (5). The methods of achieving sustainable manufacturing differ between discrete and process manufacturing. Discrete manufacturers are largely limited to minimising resource consumption and redesigning their products to use sustainable resources where possible (6). Process manufacturers are often able to keep the characteristics of their products the same but redesign their systems to use alternative sustainable feedstocks (7). Despite progress made by manufacturers, more needs to be done to meet demands of a growing population. In 2017, the European Union (EU) expanded its list of critical raw materials (CRM) to 27. These are defined as materials considered to be of high importance to the EU economy and of high risk to their supply (8). CE thinking has emerged as a means of increasing the resilience of manufacturing to disruptions in the supply of resources.

The UK-based Waste and Resources Action Programme (WRAP) charity defines the CE as "an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life" (9). The application of CE thinking to process manufacturing requires deeper consideration than discrete manufacturing, where it is simple to visualise a discrete product being reused, repaired and recycled (such as fixing a kettle). This school of thought does not lend itself to some process manufacturing products; for example, it is not possible to reuse, repair or recycle a pharmaceutical drug once consumed. However, by expanding the system to include waste produced during manufacturing (i.e. capture pharmaceuticals in waste or water streams and recover for use) and waste from the consumer (in this example human waste entering wastewater systems) it is possible to recapture the resource into the economy through waste recovery and valorisation. This also offers opportunity to increase profitability, in addition to reducing environmental pollution.

The application of emerging IDTs to manufacturing (sometimes referred to as Industry 4.0) to support the implementation of the CE has strong potential (10). However, a keyword search on the Web of Science database returns only 29 documents for both "circular economy" and "Industry 4.0", compared to 4138 and 4031 when the keywords are searched independently. This article aims to close the knowledge gap by exploring how IDTs may support CE principles within process manufacturing systems, specifically waste valorisation and process resilience.

Two process manufacturing case studies are evaluated within the field of CE. The first case study focuses on applications of CE to support waste valorisation within waste and wastewater management. For process manufacturing, 50–100% of the starting materials (and hence resources used in that system) are removed from the system *via* the wastewater. The wastewater and resources within then enter waste management bodies such as solid waste or WWTPs, or depending on the country and regulations (that may or may not be evident or enforced) may be released directly to the natural environment (11). Recovering water, energy and nutrients is an established application of CE to WWTPs (12) and readers are referred elsewhere (13) for a review of current innovations within WWTPs. However, the manufacturing environment from the CE perspective offers more inclusive considerations. Here innovative thinking coupled with new technologies enables process manufacturing plants to adapt and emerge, switching priorities from treating waste and water for reuse to manufacturing products from waste streams. The second case study demonstrates how IDTs may increase the resilience of FMCG industries and reduce resource consumption. Recent literature has demonstrated some innovative applications of IDTs to FMCG (14, 15). This case study aims to demonstrate how these technologies may be utilised within the context of CE.

Waste Valorisation Between Manufacturing Systems

There is a consensus among researchers that it is not possible to reach a fully CE, as the process of recycling will also always create waste and side products due to increasing entropy (16). Instead, the goal is to identify resources from renewable sources and to minimise the spent resource leaving the system (17). Process manufacturing systems can take this further as their waste can contain valuable material available to use as is or as a building block for a related process manufacturing environment. This is known as the cradle-to-cradle concept, where waste is both recycled and utilised as a raw material (18). Applying this concept expands the traditional CE model from a singular circular system to a series of connected circular systems, where one system's waste is another's resource. This reimagining of the CE concept is shown in **Figure 1**.

The challenge of brokering relationships between manufacturers to form innovative collaborations that find ways to utilise waste from one as a

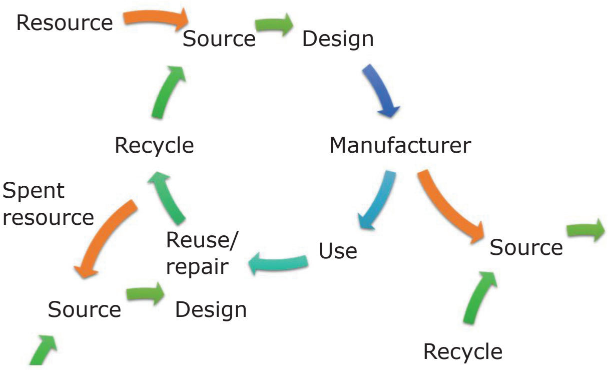

Fig. 1. Integrating the cradle-to-cradle concept within the CE model

raw material for another is known as industrial symbiosis (19–21). There are examples of support networks for industrial symbiosis, such as the National Industrial Symbiosis Programme, UK (22); Cleantech Östergötland, Sweden (23) and Kalundborg Symbiosis, Denmark (24). However, more needs to be done to make industrial symbiosis a wide-spread reality (25). There is an opportunity to utilise recent data-driven analysis and modelling advances to drive the implementation of industrial symbiosis (10). One such application is the development of data-driven models to describe manufacturing systems and enable intelligent decision-making on cloud platforms like Sharebox (a platform for physical resource sharing) (3, 26). Data-driven models can identify relationships between the system state variables (input and output) to inform on the system and make predictions on key process variables (for instance, product yield and quality) (27). By sharing and modelling a system's data, a data-driven model may evaluate the economic feasibility and environmental impact of utilising that waste as a resource. The model could further be used to evaluate multiple different systems to select the most sustainable valorisation route. For example, brewers' spent grain has multiple valorisation routes (animal and human food production, paper production, adsorbent material, enzyme production, energy source) (28). The different industrial processes to valorise the spent gains are impacted by the spent grains' characteristics (physical properties, microbial and chemical composition) (29). A data-driven model may evaluate which valorisation route is the most sustainable dependant on the spent grains' characteristics.

Traditionally waste and WWTPs were the last stage of a product's lifecycle, either treating the waste before releasing it to the surrounding environment, or with some limited reuse in system (such as heat production). Nowadays, most WWTPs recover at least some of the energy trapped in the waste and water streams and the next generation of WWTPs are targeting energy neutrality and recovery of nutrients (11). A Severn Trent Water WWTP at Stoke Bardolph, UK, illustrates the innovative work already ongoing by process manufacturers to recapture phosphorus and energy back into the economy (30). P is on the EU's 27 CRM list and although fairly common is included because of its widespread use for crop fertilisers risking future supply. Globally, 20% of the manufactured P is contained within domestic wastewater (11) and if recovered could limit the depletion of phosphate rock that is not renewable (31). The Stoke Bardolph site uses two PHOSPAQ^{TM} reactors (developed by Dutch company Paques BV) that recover approximately 736 tonne year^{-1} of phosphorous in the liquor dewatered from the sludge from municipal sewage treatment (30). Also installed on the site is an ANAMMOX® reactor and a BIOPAQ® Upflow Anaerobic Sludge Blanket (UASB), which recover ammonia and generate biogas respectively. This is then used for the combined heat and power engines, contributing 7% to the site's energy use (30). With innovative thinking, coupled with new technologies, future WWTPs could take this further, so they are not only recovering resources but also manufacturing products onsite, **Figure 2**. The energy and water recovered from the wastewater could be used to support the manufacturing processes, helping to realise a truly CE by reducing the requirement of fresh resources, **Figure 2**. There is the potential to generate a wide range of products from wastewaters including: biofuels, biohydrogen, biopolymers, single-cell protein, fertiliser, cellulose and alginic acid as well as nutrients and metals recovery (11, 32). However, there is still some way to go before these circular thinking technologies can be deployed, as the technology readiness levels (TRL) for most are below TRL5 (11). TRLs measure the maturity of technology during the stages of its development between basic principles (TRL1) and commercialised operating product (TRL10) (33). One project aiming to achieve this is the NextGen initiative, funded by the EU (34). NextGen aims to demonstrate innovative technological, business and governance solutions for water in the CE, in

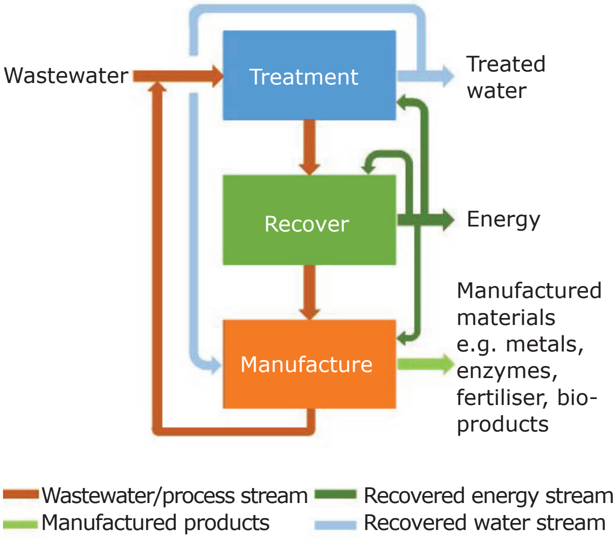

Fig. 2. Innovative WWTPs case study. Moving beyond the traditional concept of treating water so it is fit for purpose e.g. for release to the aqueous environment. Moving towards treatment plants of all sizes powered by the renewable bioenergy recovered from the waste or water and additional products where resources are recovered

ten high-profile, large-scale, demonstration cases across Europe.

Process Resilience Across Different Manufacturing Environments

Process manufacturers consume an extensive amount of resources during production processes. For example, the processing industries use 20% of the total global freshwater reserves during production (35). Towards the goal of sustainable resource use, the first steps are to investigate substituting raw materials for sustainable alternatives and to increase the efficiency of manufacturing processes to reduce the resources wasted during production. This falls under the field of 'process intensification', which is a chemical and process design approach that leads to substantially smaller, cleaner, safer and more energy-efficient processes (36). Process manufacturing systems are subject to variability throughout the system, including variations in feedstock characteristics and supply, unit operation process conditions and the waste produced by the system. This variability results in wasted resources, as manufacturers over-design their systems to limit the impact variability has on product quality and yield (37), and increases the complexity in process intensification attempts (38). As manufacturers move away from non-renewable sources towards renewable feedstocks this will become an even greater challenge for engineers (39). Previously, process manufacturing plants have been over-designed in an attempt to capture the variability within the boundaries of the plant's system (40).

Recently there have been advances in the application of data-driven modelling to better understand and optimise process manufacturing systems (41, 42). By modelling historic data, it was possible to identify and understand the effect of the variables that strongly affect the system (42). The model can then be used to make predictions on how these variables can be manipulated to reach the model's goal, defined by the manufacturer. Currently, process manufacturers collect a large amount of data from process control systems that is not fully utilised and often only used for after-the-event analysis (43). There is an opportunity to develop data-driven models from this data to investigate the cause of resource waste within the systems and ensure this waste is designed out of future systems. For example, in the biopharmaceutical industry yields can vary from 50% to 100% for no immediately discernible reason (42). Sadati *et al*. were able to develop a data-driven model from historic data that identified the control variables resulting in fluctuations in yield (42).

Data-driven models can also improve the development of affordable sensors to monitor systems that have previously been economically unfeasible to monitor. This is particularly true for the food and drink industry that is characterised by a large number of small and medium enterprises (SMEs) who face small profit margins and have limited resources to utilise new IDTs (44). For example, clean-in-place (CIP) systems (a method of cleaning the interior surfaces of pipes and process equipment without disassembly) use excessive amounts of water, chemicals and time. Cleaning is essential to ensure the equipment remains hygienic but inefficient in terms of resource use as systems are always designed to clean the materials which cause the worst fouling to the equipment (45). If manufacturers were able to model and predict the fouling behaviour of each product it would reduce the amount by which the CIP systems are over-designed, resulting in a saving of resources. An example of a sensor and data-driven model system used to reduce resource use during industrial equipment cleaning processes is presented in **Figure 3**. A data-driven model was developed to predict the point at which cleaning

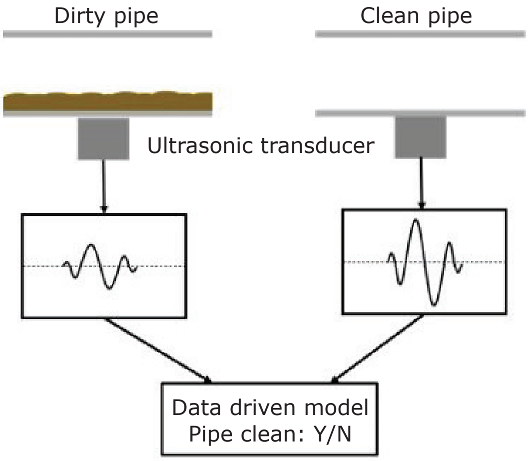

Fig. 3. CIP case study (45). Development of an ultrasonic sensor which uses machine learning to monitor and therefore optimise the cleaning of industrial processing equipment. This technology will enable the optimisation of the cleaning processes, reducing cleaning time and chemical, energy and water use

was achieved by modelling measurements from an affordable, non-intrusive ultrasonic sensor.

When aiming for sustainable manufacturing it is important to recognise that what is sustainable in one environment may not be sustainable for another. Different geographical regions and industries face different regulations and have access to different resources. The EU's rare earth minerals are depleted and there is a heavy reliance on imports, as reflected in the EU's list of CRM (8). Regions that still contain plentiful mineral reserves may face different challenges such as water stress (46). Data-driven modelling for dynamic forecasting of a range of applications has already been tested in a variety of fields (47). In the future, it may be possible for a manufacturer to model and forecast the availability and variability of the supply of resources. This will enable intelligent decision making to identify and implement the most sustainable manufacturing route dependent on available resources. By recovering, reusing, recycling and valorising waste resources it will further increase the resilience of manufacturing systems from disruptions in the supply chain.

Final Remarks

During the 20th Century, our manufacturing systems were driven by economic incentives to expand the production of goods and services, with little to no regard to the environmental impacts this caused (48). In the past couple of decades there has been a recognition by the international community that this is unsustainable and manufacturers have been pressured to introduce sustainable strategies. However, the progress made has not been sufficient and the resources required to support the global population now exceed those available (49). This article has offered a brief overview of the applications of data-driven models (a key IDT) to support the CE principles of waste valorisation and process resilience. Data-driven modelling applications for analysis, decision making and forecasting were presented in the context of two process manufacturing case studies. A gap currently exists between the research fields of CE and Industry 4.0, as demonstrated by the limited number of joint publications between these fields. Therefore, there is great potential for research demonstrating the application of further IDTs (for example internet of things, cyber-physical systems, cloud manufacturing, cognitive computing) to drive the CE.

Acknowledgements

Rachel Gomes would like to acknowledge the support of Engineering and Physical Sciences Research Council (EPSRC) (grant number EP/K014161), Cloud Manufacturing – Towards Resilient and Scalable High Value Manufacturing and EPSRC (grant number EP/M022234/1), Biotransforomics: Bioanalysis to Engineer Understanding in Wastewater Treatment. Nicholas Watson would like to acknowledge the support of Innovate UK (ref:132205). Oliver Fisher would also like to acknowledge the University of Nottingham Faculty of Engineering for his PhD scholarship.

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