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Review

A Regenerative Business Model with Flexible, Modular and Scalable Processes in A Post-Covid Era: The Case of The Spinning Mesh Disc Reactor (SMDR)

Emma Anna Carolina Emanuelsson [1], Aurelie Charles [2] and Parimala Shivaprasad [1,*]

[1] Department of Chemical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, UK; eaep20@bath.ac.uk
[2] Department of Social and Policy Sciences, University of Bath, Claverton Down, Bath BA2 7AY, UK; ac697@bath.ac.uk
* Correspondence: ps784@bath.ac.uk

Abstract: With stringent environmental regulations and a new drive for sustainable manufacturing, there is an unprecedented opportunity to incorporate novel manufacturing techniques. Recent political and pandemic events have shown the vulnerability to supply chains, highlighting the need for localised manufacturing capabilities to better respond flexibly to national demand. In this paper, we have used the spinning mesh disc reactor (SMDR) as a case study to demonstrate the path forward for manufacturing in the post-Covid world. The SMDR uses centrifugal force to allow the spread of thin film across the spinning disc which has a cloth with immobilised catalyst. The modularity of the design combined with the flexibility to perform a range of chemical reactions in a single equipment is an opportunity towards sustainable manufacturing. A global approach to market research allowed us to identify sectors within the chemical industry interested in novel reactor designs. The drivers for implementing change were identified as low capital cost, flexible operation and consistent product quality. Barriers include cost of change (regulatory and capital costs), limited technical awareness, safety concerns and lack of motivation towards change. Finally, applying the key features of a Sustainable Business Model (SBM) to SMDR, we show the strengths and opportunities for SMDR to align with an SBM allowing for a low-cost, sustainable and regenerative system of chemical manufacturing.

Keywords: spinning mesh disc reactor; reaction intensification; flexible manufacturing; resilient supply chain; sustainable business models

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1. Introduction

Applying the key features of a Sustainable Business Model (SBM) [1] to a chemical manufacturing innovation called Spinning Mesh Disc Reactor (SMDR), this paper shows the strengths and opportunities for SMDR to align with an SBM by creating a low-cost, sustainable and regenerative system of chemical manufacturing. The chemical and process industries are responsible for the creation of materials, which are processed into products for multiple consumer markets using clean, safe and economical manufacturing technologies [2]. The global chemical industry (including pharmaceuticals) accounts for a significant share in world trade and economics, as it is a key driving force for innovation and smart growth in sectors such as construction, transport, energy and health [3]. Achieving economic sustainability has always been one of the top priorities for the chemical sector, but there is a shift to also include environmental sustainability which requires the intervention of new technologies and business models [2–4]. The design of existing manufacturing technologies limits their application for novel processes like bio-transformation, multi-catalytic reactions, synergistic processing (combination of two or more energy forms) and continuous processing in fine chemicals manufacturing [5,6]. Additional challenges such as poor energy efficiency and production of waste by-products have further highlighted the need for innovative technologies which can drive sustainability in the chemical sector.

Academic research to date have reported several novel chemical reactor designs such as microchannel, oscillatory-baffled reactor, rotating packed bed reactor and spinning disc reactors which have shown to improve resource efficiency (both monetary and environmental) on a laboratory scale, with significant implications for the fine chemical industry [7–10]. The Spinning Mesh Disc Reactor (SMDR) is one such reactor developed by the Emanuelsson research group, which has shown potential for efficient and scalable production of fine chemicals [11–14]. The research has now been incorporated as SMDR Limited, to explore the commercial opportunities for the reactor in the pharmaceutical sector. With over 10 years of research into the SMDR and an intensive market assessment, we have identified the key attributes required in a commercial catalytic reactor as:

- Fast reaction rates and high selectivity to minimise by-products
- Suitable for shear sensitive catalysts (enzymes and microbes)
- Small and flexible design, easy scale-up and low capital investment cost
- Allow recovery and re-use of expensive catalysts

The aim of this article is to present our findings from extensive global market research for novel reactor designs and to show how SMDR can feed into an SBM. We have chosen the SMDR technology as a case study of a newly developed reactor design, which allows for flexible manufacturing and easy scale-up. The results from the market research will be analysed based on the characteristics of the SMDR to identify the opportunities and barriers for commercialising the SMDR. Finally, we will demonstrate the strengths and opportunities of the SMDR for regenerative manufacturing by exploring the extent to which its innovative criterion matches the features of SBM to enable local, flexible and resilient manufacturing.

2. Current State of Catalytic Reactors

2.1. Manufacturing Processes

Batch catalytic reactors consist of a cylindrical vessel with one or more stirrers mounted on a central shaft to enable mixing of reactants required for product formation [10]. They are widely employed in chemical industries as they are easy to operate and economical for bulk chemical production. Batch catalytic reactors have been used in fine chemical industries globally for close to 500 years with little or no change to the reactor design. Meanwhile, in 2019, the total revenue of the chemical industry worldwide stood at some 3.94 trillion U.S. dollars [15].

While batch reactors are easy to operate and a cost-effective solution for operation on a small scale, they are met with significant challenges when it comes to multiphase reactions and reactor scale-up. Unlike bulk chemicals, pharmaceutical products are produced at a scale of 1000 to 10,000 tonnes per annum [16]. Scaling-up production from the scale of the laboratory to mass production is associated with two main challenges:

1. Processing time for production at scale is longer compared to laboratory scale processes. This leads to catalyst degradation and deterioration of product quality over time resulting in reduced productivity of the process.
2. Laboratory scale productivity is optimised in equipment with lower volume capacity. However, production at scale is carried out in large tanks or vessels which affects the homogeneity of the finished product and increases the energy cost required to mix the entirety of the reaction solution.

Modifications to the traditional batch reactor design have improved productivity, but it remains unsuitable for shear sensitive catalysts, such as enzymes, resulting in catalyst de-activation. Other reactor configurations like the packed bed reactor and bubble column reactors have shown better performance for multiphase reactions with improved catalyst recovery, but are however still limited in terms of high heat and mass transfer resistance upon scale-up [17,18]. Hence, there is a need for multi-functional reactors and alternate processing methods which can alleviate intermediate, inefficient processing steps and reduce the need for energy intensive downstream product purification.

Catalysts are an essential component for producing chemicals on an industrial scale as they increase the rate of a reaction without being consumed. They are either suspended in the solution (dissolved or as particles) or immobilised on a surface. Catalytic processes accelerate product formation resulting in higher product yield and reduction in energy costs. While 80% of basic chemicals are produced catalytically, only 20% of fine chemicals like pharmaceutical intermediates employ catalysts in their production process [19]. This implies that most of the fine chemical production is based on a direct scale-up of laboratory scale synthesis procedure, which results in by-product formation often exceeding the production of the target chemical. The lack of catalyst utilisation is not due to the lack of catalytic process but mainly due to the novelty and the related uncertainty of using catalysts in chemical reactions. Hence, they are regarded as an important tool to achieve both sustainability and profitability in the fast-growing fine chemical industry with a need to improve process efficiency.

2.2. Socio-Ecological Challenges

With an increasing awareness about resource use and government regulations, chemical industries are fast realising the need to change their manufacturing processes to align with sustainable strategies.

Current manufacturing in fine chemical industries largely employs catalytic materials that are expensive, toxic or harmful to both environmental and human health [20]. Biochemical catalysts such as enzymes are a greener alternative as they are highly specific in nature, require milder operating conditions, resulting in lower waste formation and energy requirements. The key challenge however is that enzymes are expensive catalysts in its recovery and re-use which limits their application in the fine chemical industry. Enzyme immobilisation has shown to enhance the cost-efficiency of the bio-catalytic process since the catalytic activity is maintained for a longer duration which allows for recovery and re-use of enzymes [21]. However, utilisation of immobilised catalysts requires increased mixing, hence increasing energy costs and catalyst disintegration, which until now limits the application of the current batch reactor design.

Additionally, batch reactors are not flexible on the production and consumption sides of the supply-chain as they are not designed for: (i) de-centralised processes where resources can be processed close to the place of extraction, and (ii) being responsive to demand-led changes driven by social and political shocks on the supply-chain, such as the COVID-19 crisis. In effect, post-WWII production and consumption patterns were mainly determined by the availability of raw materials (mainly petroleum based) resulting in manufacturing being restricted to certain geographical areas rich in raw materials [22]. To enable the transition towards bio-economy and renewable resources, it is crucial to develop flexible manufacturing technologies which are able to operate at different scales and in different geographical settings.

However, technical innovations alone cannot accelerate the transition towards sustainable technologies. One of the key barriers to change is the process of regulation in the fine chemical industry. These are often well established for existing manufacturing technologies and any process change is accompanied by expensive and time-consuming regulatory approval. Policies for increased incentives for companies adopting and investing in sustainable technologies, cost-effective regulation, de-risking/increased public funding for new research, recognition from the society creating a demand for sustainable technologies can overcome the barrier to change [3]. Additionally, there is a knowledge gap about using these innovative manufacturing technologies due to the lack of skills required to operate and monitor these new systems, hence decelerating technology transfer from research labs to industry.

Hence, there is a need for a cost-efficient reactor that has the potential to support a range of catalytic reactions at varying production capacities without additional modifications to the reactor design.

3. SMDR as a Case Study for Sustainable Reactors

Process intensification (PI) is a recent development in chemical processing with the potential to facilitate a quantifiable change in the conventional manufacturing practices of chemical industries. This is usually accompanied by a reduction in the size of the apparatus, energy consumption and/or waste generation, resulting in the sustainable development of process industries [12]. On a macroscale, PI has led to a new generation of reactors and processing methods, allowing for better control of the reaction pathways at meso and molecular level leading to: (i) enhanced reaction rate, (ii) increased selectivity of the product and (iii) scale-up of novel chemistry on a commercial scale [13].

Among the new generation of PI reactors, the Spinning Mesh Disc Reactor (SMDR) has shown potential to incorporate the fundamental domains of PI and facilitate reaction intensification. The reactor builds on the nearest state-of-the-art such as the spinning mesh disc reactor (SDR) and Chromatotron (thin-layer centrifugal chromatography). The SMDR is a flexible, modular and scalable reactor for catalytic reactions. The reactor consists of a rotating disc that has a cloth with immobilised catalyst resting on top (Figure 1). The liquid feed is distributed at the center of the disc, and the spinning motion of the disc allows the formation of a thin liquid film, over and within the cloth. This increases the contact time between the liquid feed and the catalyst, achieving high mass transfer and thus fast reaction rates. The cloth protects the catalyst from shear forces and can be easily removed from the disc at the end of the reaction to be then reused multiple times. Reaction scale-up can be achieved with minimum capital investment and a small footprint, by simply adding more catalyst cloths onto the disc, thus eliminating the need for a reactor re-design for higher feed throughput.

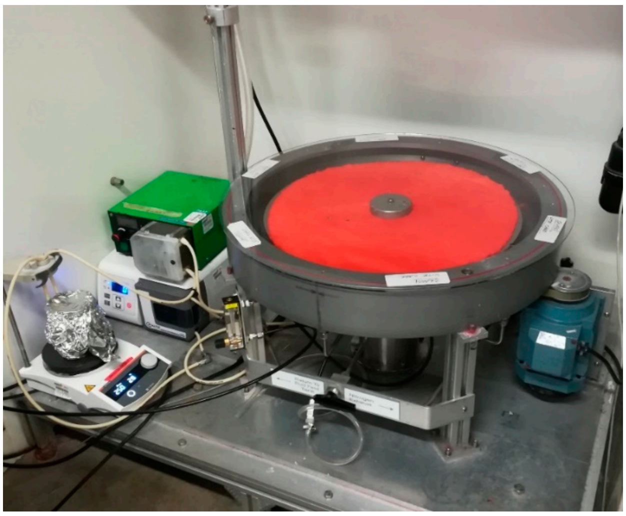

Figure 1. Prototype of the spinning mesh disc reactor.

3.1. The ICURe Journey: Global Market Research for the SMDR

The SMDR is able to achieve fast reaction rates, improve catalyst recovery, can be easily scaled-up and is applicable to a range of reactions on the lab scale. Such performance encouraged the Emanuelsson Research group to investigate the commercial prospects for the reactor. We conducted extensive market research and customer discovery for the SMDR through the ICURe (Innovation to Commercialisation of University Research) program funded by Innovate UK. We engaged with more than 100 companies around the globe in key chemical sectors such as cosmetics, pharmaceuticals, specialty chemicals and chemical reactor manufacturers. The main objective was to identify the current challenges in chemical manufacturing (customer welfare loss) and to understand whether the SMDR had the potential to alleviate these challenges to improve processing efficiency in chemical industries (customer gains). The general observation across all sectors was that there is a drive towards implementing sustainable solutions to processing and product development, either through utilising raw materials derived from renewable resources or by adopting alternate processing technologies. Replacing existing chemical catalysed processes with enzyme catalysts was another common interest observed across the fine chemical industry. The key drivers among the companies who were actively taking steps towards implementing change were found to be at the organisational level (company strategy and vision towards reducing carbon emissions), at the policy level (government regulations and incentives), and at the market level (perception of clients and competitive advantage over competitors).

However, it was observed that there is still a gap between the rate at which innovative process technologies are reaching the market and their implementation on a commercial scale. Some of the common reasons were found to be:

1. *Cost of change:* Chemical sectors such as pharmaceutical and cosmetic industries have to comply with stringent regulations and any change in the existing process requires lengthy and expensive regulatory approvals. The cost of production downtime often outweighs the benefit of higher process efficiency and product yield.
2. *Initial capital expenditure (CAPex):* The current batch reactor technology for manufacturing in fine chemical industries has been in use for decades and is well established. Adopting new reactor technology would require capital investment for procuring and installation of these reactors to replace the existing reactors. The reactors themselves are depreciating assets and they have no resale value. Medium scale fine chemical companies in the US and India stated that it was not beneficial for the company to invest in a low TRL technology with high uncertainty when they were able to generate profits with their existing reactor capabilities. These companies are improving the efficiency of the batch reactors by investing in improved impeller designs as they can be retrofitted to the batch reactor with minimum disruption to the process. However, most companies in Europe and large-scale companies in the US and India were investing in new reactor technologies despite a significant capital investment. The reactors were being employed for either newly commissioned processes (with no existing production facility) and/or for niche chemicals of high value with lower production demands. Most companies acknowledged the potential of these reactors for the production of high value chemicals as they improve product yield, while also reducing the operating costs for the process.
3. *Knowledge gap:* PI reactors have shown great potential to be implemented on a commercial scale owing to their success in laboratory scale operations. Some PI reactors like the micro-channel reactor are increasingly being used for commercial operations but are not often publicised due to competition and confidentiality. PI reactors are known to be inherently safer than batch reactors due to lower reaction volumes. However, conversations with companies showed that there have been safety related incidents with PI reactors due to the lack of specialist knowledge required to optimise and operate these reactors. These factors have affected the commercial success of PI reactors.
4. *Motivation for change:* This was one of the major challenges identified by chemical companies for replacing batch reactors. Companies involved in manufacturing new reactor technologies mentioned that it was hard to spark enthusiasm among the top management in chemical companies as they are the decision makers. The interactions also showed that the US was a tough market for new reactors as there is no incentive or drive for a process change. On the other hand, the Asian–Pacific region is a fast-growing market for emerging reactor technologies due to large manufacturing facilities and most reactor manufacturers have found traction through clients from this region. The European market was found to be equally responsive to change as it is

an active research hub for emerging reactor technologies incentivised by government and company policies for sustainable manufacturing.

3.2. Sustainable manufacturing: Opportunities for the SMDR

3.2.1. Affordability and Market Outreach: Low Capital Investment

The Active Pharmaceutical Ingredients (API) division within the pharmaceuticals sector is identified as the immediate target market for the SMDR. APIs are high value products that determine the therapeutic nature of the medicine (end product). The global API market is valued at USD 165 billion and is growing at 6.4%. Asia–Pacific has the largest market share while Europe constitutes 22% [23]. Similarly, the global market for emerging reactor technologies is valued at USD 1.2 billion with Asia–Pacific, Europe and the UK constituting a significant proportion of the market share [24].

The common manufacturing challenges companies have in this sector are: catalyst recovery, product scale-up and slow reaction rates. Market research showed that pharmaceutical companies involved in API production are investing in PI reactors, due to benefits such as low capital investment, high productivity and inherent safety. India (12.3%) and China (53.2%) are fast growing markets for low cost APIs and are the likely early adopters of the SMDR due to an increased purchasing power of pharmaceutical companies and a growing interest in emerging reactor technologies [25,26].

The current business model of equipment procurement is associated with the initial investment for procuring new reactors. This is a key risk for chemical companies due to the uncertainty associated with the new PI reactors. At SMDR Limited, we have envisaged a subscription model, similar to the Nespresso business model, to reduce this barrier to market entry. For a monthly subscription fee, pharmaceutical companies will be able to lease the reactor prototype accompanied by an optimised protocol for the production of API. The clients will also receive support in the form of remote reaction monitoring and catalyst cloth replacement for an additional service fee, which is a recurring revenue for SMDR Limited. During market research, we found that adopting this model for the SMDR would minimise the product lead time and the cost to our clients and hence reducing the barrier for market entry. This business model has the potential to disrupt the existing sales model of the reactor manufacturing industry as the clients no longer have to pay upfront capital and reducing the risk of adoption of a new technology. Additionally, it has been shown that the construction period for PI reactors is reduced from three years to one year, resulting in 35% higher net present value for these modular reactors [27]. These economic benefits make the SMDR a competitive reactor technology.

3.2.2. High Productivity and Scaling Up

One of the major drawbacks of the batch reactor is that the scale-up in production requires an increase in the reactor size, which leads to higher mixing costs and heterogeneity of the product due to large reaction volume. Unlike the batch reactor, the SMDR can be scaled-up through ‘numbering-up’, i.e., by adding multiple catalyst cloths on top of the disc or adding multiple discs to the central shaft, eliminating the need for a complete reactor re-design. The reaction in the SMDR takes place within the thin liquid film on the disc and hence allows for operation with a wide range of feed throughput. This also reduces the inconsistency in the product quality as there is uniform contact between the reaction mixture and the catalyst cloth. For example, a 35% increase in productivity was observed in the SMDR for an enzyme catalysed kinetic resolution of racemic alcohol compared to the batch reactor [12]. This shows that the productivity in the SMDR is not affected by process scale-up, unlike the batch reactor. The Emanuelsson research group has shown that for lipase catalysed tributyrin hydrolysis, the reaction rate nearly doubled as the number of catalyst cloths increased from one to four cloths for a given initial reactant concentration (Figure 2a).

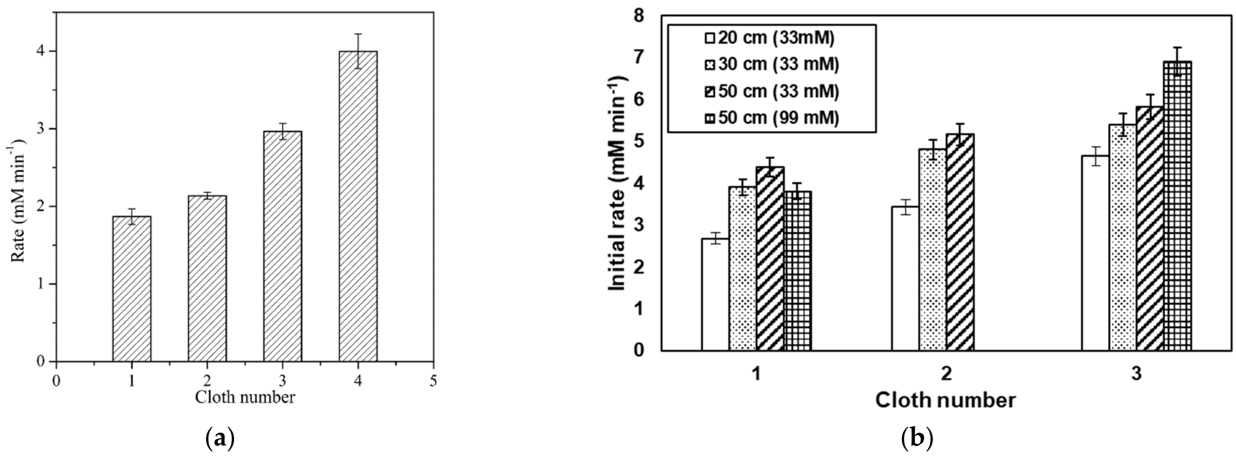

Figure 2. (**a**) Effect of increasing cloth size on reaction rate in the SMDR "Reprinted from Increasing reaction rate and conversion in the spinning cloth disc reactor: Investigating the effect of using multiple enzyme immobilized cloths, 255, Xudong Feng, Darrell Alec Patterson, Murat Balaban, Emma Anna Carolina Emanuelsson, Chemical Engineering Journal, 356–364, © (2021), with permission from Elsevier", (**b**) Effect of increasing cloth size and cloth number in reaction rate in the SMDR "Reprinted from Investigating the effect of increasing cloth size and cloth number in a spinning mesh disc reactor (SMDR): A study on the reactor performance, 147, Parimala Shivaprasad, Matthew David Jones, Paul Frith, Emma Anna Carolina Emanuelsson, Chemical Engineering and Processing, 107780, © (2021), with permission from Elsevier".

In another study, a comparison between 'scale-out' and 'numbering-up' of the SMDR was investigated using varying disc/cloth size and cloth numbers (Figure 2b). It was observed that a simultaneous increase in the catalytic cloth size and cloth number led to increased productivity for high input feed concentration. For lower initial feed concentrations, it was observed that the productivity achieved using a single 50 cm catalyst cloth was similar to that using obtained using a stack of three 20 cm cloths [11]. This demonstrates that the SMDR can either be scaled-up or scaled-down to allow for varying production capacities depending on the process requirements.

3.2.3. Inherent Safety

In addition to improving process efficiency, the SMDR is benign by design due to miniaturisation of the chemical process. Working with chemists at the reaction development stage allows us to take an inherently safer and ethical approach both when developing new chemistry and for reactor scale-up. We are guided by the 12 principles of green chemistry and engineering and have implemented most principles (either through selection in the initial chemistry development, or optimisation in the reactor). For example, the following principles were applied: using safer solvents; better atom economy; prevent waste; maximise energy, time, mass and space efficiency; catalysis; inherent safer design and design for separation.

The reactor is characterised by small functional volumes exposed to reaction conditions such as high temperature and pressure, minimising the consequences in case of a mishap. This is also safer for reactions which utilise hazardous chemicals, minimising the quantities exposed to harsh reaction conditions. The SMDR also promotes distributed manufacturing, where production in small volumes takes place in multiple locations instead of a central large production facility. This further reduces the risk of transporting toxic chemicals and safety issues related to their storage. The long term goal would be to enable on-demand production for immediate consumption, reducing the need to store inventory and the product.

3.3. A Regenerative Approach for Resilient Manufacturing

In the management literature around clean production, Sustainable Business Models (SBM) have emerged over the past few years as viable models able to embrace the environmental and social challenges for sustainable innovations [1,28]. The advantages of the SMDR business model are numerous in that respect, whether it is in terms of affordability, economic efficiency, safety, inclusivity, or environmental sustainability. Yet, from the global market research described above of potential companies willing to adopt sustainable technologies, a few entry barriers persist including the initial investment required, the knowledge transfer required to implement innovative technologies successfully, and the lack of corporate motivation that impedes a successful uptake of such technologies to replace traditional methods of chemical production. As will be discussed now, we will assess the extent to which SMDR is a successful SBM able to overcome such entry barriers.

According to the literature review of [1], the feature of SBMs for manufacturing innovations are namely (1) sustainability, (2) circular economy, (3) value chains, (4) value creation, (5) information technology, (6) core values, (7) organisational values, (8) performance management and (9) stakeholder engagement (partnership, participation, communication and consultation).

(1) Sustainability: The resilience of a successful SBM comes from its ability to make strategic business decisions in reaction to social, economic and environmental shock to sustain the innovation in the long-run [1]. Here, SMDR provides a modular and regenerative approach to fine chemical production. SMDR is able to fulfil its long-term goal of producing on-demand, at the point of resource extraction, for immediate consumption. Such context-based technology means that, in the event of external shocks on the supply chain as for example experienced with the Covid crisis, such shocks will be absorbed by the regenerative supply chain, able to answer quickly to supply changes by scale-up or down with limited costs.

(2) Circular economy: Reducing waste and managing resources as efficiently as possible to narrow the energy and material loops is key to a successful SMDR [1]. Raworth [29] has explained the ways in which a circular economy enhances industrial manufacturing with a regenerative system that minimises the loss of biological and technical nutrients. The SMDR includes the use of biological components and processes that are inherently safe, as guaranteed by the application of the 12 principles of green chemistry (see point c above). The resulting effect on the circular system is that human interactions with the production process are safe, thus minimising the negative impact of chemical production on human health and biodiversity. The technical nutrients within the SMDR process include the catalyst, tailor-made to production requirements, and the cloth on top of the reactor that can be re-used in subsequent production cycles. The resulting effect on the circular system is the reuse of the cloth, which can also be adjusted to the scale of production.

(3) Value chains: A successful SBM nurtures the value chain starting with resources, suppliers, customers, support activities, and input activities [1]. A main ecological challenge with traditional batch reactors is that by-product formation often exceeds the production of the target chemical. However, with the SMDR process, production can be made on site and on-demand, shortening the supply chain to its direct output requirements, thus cutting down on transportation costs and on the storage of chemicals with its potential environmental damages.

(4) Value creation: The concept of "value" in SBM here relies on the link between corporate strategy and intangible assets that create value in the long-run [1]. Such intangible assets include finance, manufacturing, intellectual property, human capabilities, social and natural relationships. Impact research would be needed here to assess the impact of SMDR on value creation at the implementation stage, but feature (1) to (3) provides a sound theoretical grounding for value creation in the long-run.

(5) Information technology: Innovation in IT to support the manufacturing innovation in modelling, managing, and controlling its impact on ecosystem processes [1]. The SMDR aligns with "Industry 4.0" to support smart manufacturing through reactor automation, providing improved control on product quality.

(6) Core values: Interdependence, reliability, loyalty, commitment, consistency, efficiency, creativity, inclusivity, respect and positivity are core values of a successful SBM [1]. Inclusivity of all potential producers is possible with a subscription system allowing the SMDR to overcome the main entry barriers of the initial investment and the knowledge transfer necessary to make the SMDR operational on a small and large scale. Local producers in the Global South, often overpowered by the interests of transnational corporations and governmental pressures could therefore have easy access to such technology. For example, in the Democratic Republic of the Congo, a coalition between transnational capital and the Congolese state has held back locally led processes of mining mechanisation [30]. Access to simple, modular, and regenerative technology such as SMDR could empower local producers to process and scale-up mining output locally.

(7) Organisational values: Employee, social and environmental safety, responsibility, profitability and drive for results are key organisational values of an SBM [1]. Such values will depend on the organisation in which SMDR is implemented, but the inherent safety (c) and high-productivity (b) of SMDR is conducive to enhance an SBM.

(8) Performance management: A successful SBM needs to incorporate performance measurement into all aspects of industrial processes including service, business management, quality, productivity and efficiency [1]. Performance management will again depend on the organisation in which SMDR is implemented, but with a lease-system allowing to monitor its implementation and efficiency, there is again scope for SMDR to enhance an SBM.

(9) Stakeholder engagement: Partnership, participation, communication, and consultation are key elements for a successful SBM. As such, the key features of SMDR (a) to (c) are well-aligned with the current Sustainable Development Goals [31], especially Goal 9 Industry, Innovation and Infrastructure; Goal 11 Sustainable Cities and Communities, and Goal 12, Responsible Consumption and Production. There is therefore scope to engage governmental and international support to implement SMDR in both the Global South, such as sub-Saharan Africa [32] and the Global North.

4. Conclusions

The chemical process industry has started to make progress towards adopting innovative reactor and process technologies with the potential to improve the sustainability of manufacturing. Process intensification reactors such as the SMDR have shown promising results on the lab scale to improve the overall productivity and sustainability of processing for the fine chemical sector. The SMDR can be scaled-up with minimum modifications to the reactor design and allows for recovery of expensive catalyst, reducing the need for energy intensive purification steps. Market assessment for the SMDR identified the pharmaceutical sector to be the immediate target market due to benefits such as high product quality and low turnaround time. Although there is a drive towards green technologies among chemical companies, key barriers to change such as cost, regulations and lack of technical knowledge have resulted in the slower implementation of innovative chemical reactor designs. The pandemic has highlighted the need for resilient and flexible manufacturing technology to minimise the risk of lean supply chain of pharmaceuticals. The modular and flexible characteristics of the SMDR provide a pathway for pharmaceutical companies to manufacture important intermediates locally, eliminating the need for wide scale imports. A combination of government policies, regulatory and investment support in line with the SDGs is necessary for commercial implementation of technologies like the SMDR which have demonstrated sustainable advantage but are associated with higher risk compared to existing conventional technologies. Finally, from the application of SMDR to SBM, despite promises in terms of sustainability, circular economy, stakeholder engagement, core values and value chains it remains that a successful implementation of SMDR as an SBM relies on the organisational values in which SMDR will be implemented.

Future research on impact assessment of SMDR implementation at the organisational level is therefore needed.

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