WORLD MANUFACTURING FOUNDATION

BACK TO THE FUTURE

EMERGING TOPICS FOR LONG-TERM RESILIENCE IN MANUFACTURING

MODULAR MICROFACTORIES

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For more information on the project and to read other topic-focused whitepapers that are part of the initiative, please visit https://worldmanufacturing.org/report/back-to-the-future-emerging-topics-for-long-term-resilience-in-manufacturing/

INTRODUCTION

The global Covid pandemic has created a new reality for manufacturing companies. It poses many problems such as employee safety, broken supply chains, lack of direct customer outreach, and production reduction or complete shutdown. Large and small manufacturing companies have been hard hit. Companies now require a new competitive edge to maintain and increase productivity, keep people safe, facilitate new ways to work, engage customers virtually, and to develop new business models. In this whitepaper we look at how microfactories can help to meet this challenge. We first try to define what a microfactory is, followed by an analysis of the benefits and advantages that they provide. The goal of the whitepaper is to provide a short practical guide for managers who are making strategic decisions on how to adapt to the new manufacturing realities. We have added several case studies in the appendix to showcase some of the more successful implementations of microfactories. The paper is the result of several webinars and various discussions held during the summer of 2021 with a very talented group of companies and universities from 10 countries. We first outline the key issues to be addressed, and secondly, we outline the opportunities for action followed by some key recommendations.

CONTEXT: What is a modular Microfactory?

In looking at the literature, the concept of a microfactory was first coined in Japan in the 90s but has since evolved to encompass a broader definition. Initially, a microfactory was defined as a highly automated small- footprint facility which could be located in a small room to produce parts or consumer products. Key characteristics included a range from a desktop-sized footprint to a small shop, to a 5,000 sqm factory[1].

More recently, the term microfactory has evolved to include larger footprints with highly modular flexible and automated facilities to produce small-batch electric vehicles, for example. Several companies such as Local Motors in the US, Street Scooter in Germany and Arrival in the UK have a strategic focus on this type of manufacturing.[2] Key characteristics include reconfiguration and recuse of production systems.

An additional characteristic of microfactories is that they can provide supply security because they are relatively self-contained and do not rely as much on global supply chains. For example, they use additive manufacturing for certain parts.[3] Some of the key drivers for local production independence include:

- Green production
- Efficiency for small scale production
- Flexibility and need-driven
- Personalisation
- Technology and cost optimisation
- Expansion of skill sets
- New players in the market with innovation propositions

Small-batch production with a high capability for innovation can be supported with ultrafast and auto-adaptable systems with complex digital infrastructure, which can be self-reliant and meet the challenge of supply security. In this paper, we examine more specifically the key elements which make microfactories successful. Finally, we provide several examples in the appended case studies to demonstrate how these principles are applied.

Modular Products & Complexity Management

Modularity is very critical for the microfactory approach. Modularity is defined as integrated planning of product platforms and modules where:

- **product platforms** include different products with optimised interfaces and commonalities. Product platforms generally have an architectural approach, with interfaces, specifications, processes, bill-of-material structure and cost.
- **modules** provide common and/or replicable elements with defined functionality and standardised interfaces. Modules can have exchangeable variants which can be used in various product platforms.

Complexity management within whole product life cycle is one of the most important issues for microfactories. Modular products are essential, with well-defined product platforms and modules. Otherwise complexity would be the main obstacle to successful implementation.

Adaptive Design & Manufacturing

Rapid Production Pivoting has been demonstrated as a valuable feature of microfactories, and one which is often aided by Additive Manufacturing (3D Printing) technologies. Microfactories are often comprised of self-sufficient sections which facilitate alterations to the production line without the need for full line reconstruction. This allows for the rapid adaptation from one product to another in a shorter period of time. The Covid-19 pandemic has resulted in many examples of this, from 3D- printing labs and design studios producing PPE for hospitals onsite, to modular self-sufficient manufacturing concepts such as Project Carola for Mask Manufacturing.[4] The ability to rapidly pivot manufacturing lines across a multitude of products can allow for greater company agility, and reduced costs associated with producing multiple product lines.

Emergency Production has been highlighted as a major benefit of MMFs for short-term relief and response. Modular and self-contained manufacturing platforms can be utilised to provide relief for an affected area with minimal infrastructure, or in areas with poor access to heavy goods supply chains. This can enable rapid relief efforts for producing medical equipment and spare components onsite in cases of natural disasters, warzones and, as we have recently witnessed, pandemic-stricken localities. The small size of these MMFs is also commonly aligned with standardised shipping standards to facilitate rapid deployment to these areas of need. Some examples of components produced as emergency relief in 2020 are ventilators, respiratory equipment, test swabs, and protective facemasks.

Rapid Iteration of product designs is often one of the costliest aspects of production; whether in polymers, ceramics, composite or metals, there are inherent costs associated with conventional mass production lines, often requiring costly static tooling such as moulds and fixtures. Microfactories can facilitate a shorter 'design-test-iterate-produce' pipeline through the replacement of much of this single-purpose tooling with more agile techniques such as additive manufacturing and smart robotics. In addition to rapid iteration, there are also cost benefits associated with an MMF, such as reassignment of equipment from, for example, discontinued products, to new products, without the need for significant capital investment and lengthy line redesigns. This is particularly applicable to robotic modules, which can be reprogrammed and serve in a large array of applications, from pick-and-place, to welding, coating, printing and packing.

Local & Decentralised Manufacturing

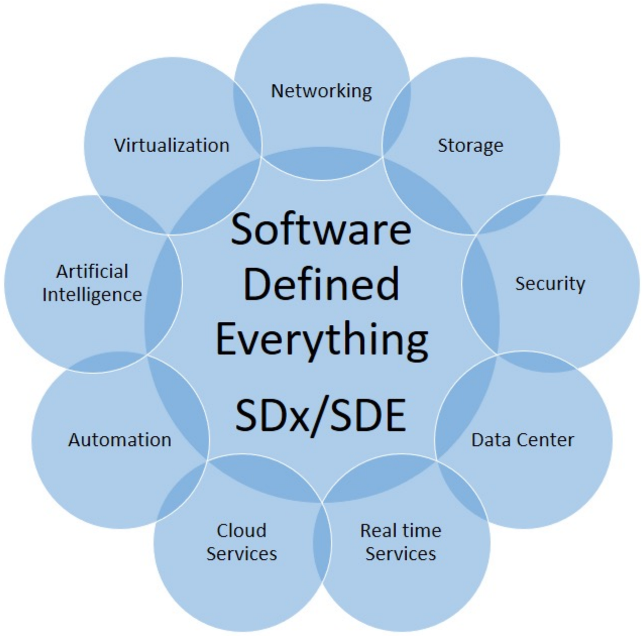
Reduced Transportation costs and a simplified supply chain are major benefits of local or onsite production of goods, both from a cost and an environmental perspective. It is more and more common in the globalised economy for products to be manufactured in several different locations around the globe and assembled in a centralised facility. This is frequently employed by the electronics, automotive and aerospace industries as a cost-saving measure, outsourcing labour-intensive tasks to lower-cost labour forces, and returning the components to the host country for assembly or final packaging. Whilst this model has the potential for cost savings in large volume production, the benefits of this model for small- to medium-scale production is less prominent. It also carries with it a heavy CO^2 footprint, as goods are transported large distances by air and sea. With ever-tightening restrictions on CO^2 increasing the cost of fuel, local and onsite production of goods is becoming an increasingly cost-effective solution for companies.

Supply Chain Resilience

Supply chain disruption was a major occurrence during the initial months of the global pandemic response. Border and premises closures precipitated a halt to the globalised supply chains on which many companies relied. For the medical supply chain this resulted in mass shortages of PPE and disposable medical components, from gloves and masks to respirators and ventilators. In many cases, alternative supplies were used to fill the gap while the major supply lines were re-established. Much of this disruption was amplified due to the concentration of manufacturers of PPE in South-East Asia, particularly China, which was one of the first regions to impose movement restrictions on its population. In many cases, local supply chains found alternative sources of supply to maintain medical operations, an excellent example of this being the use of snorkelling masks and 3D printing to assemble respiratory aids for patients in ICUs in Italy and Spain. This took advantage of the excess supply of snorkelling equipment from the shut-down tourist industry. Multiple small but agile manufacturers were able to repurpose existing equipment, such as 3D printers, to bridge the gap in the supply chain at very short notice, demonstrating the agility and flexibility of these types of manufacturing systems. This approach then spread to other countries as the epicentre of infection changed, with each applying their own unique approach to suit the local need and available supplies.

Key Role of Digital Technologies (Baris)

In order to enable microfactory solutions, integrated digital technologies are the critical ingredient. Digital technologies are more intertwined today, and Software- Defined Everything (SDx) infrastructure is very helpful for reducing silos in terms of dedicated hardware or equipment. This allows managing the manufacturing and automation systems in an agile way without manual configuration. Hence, the focus is more on application programming interfaces (API's).[5]



Interoperability & Digital Twins

Standardised hardware interfaces and software interoperability ensure easy (re-) configuration and a quick “plug-and-produce” ramp-up of the production of integrated components and modules. In that context, several standards such as OPC UA, e.g., for skill-based engineering and control on field-device-level, or Module Type Package, e.g., for orchestrating all process units in a modular plant, are currently realised to ensure cross-vendor interoperability.

Digital Twins as a digital representation of physical assets (Asset Administration Shell for Industry 4.0)[6] connect the physical with the virtual world and support both the engineering and operation of modular microfactories. They reduce lead times and ensure flawless operation right from the start, through digital engineering and virtual simulation, commissioning, etc. And they ensure high-quality operation and flexible yet reliable production, e.g., through process optimisation and predictive maintenance. They can also be used to collect data along the entire product life cycle, which opens up new end-of-life scenarios, e.g., with remanufacturing, and refurbishing services in microfactories close to customers.

Decentralised Autonomous Systems with Embedded Intelligence

Virtual simulation and real-time control of the IoT-based "cyber-physical" production system – empowered by decentralised technical intelligence with local sensors, actuators, and computing "on-edge" – enable autonomous processes. Robots as universal tools play an important role for the flexibility and adaptability of a modular, reconfigurable production system. Artificial Intelligence and machine learning as performance-enhancement tools – e.g., helping robots to autonomously recognise, pick and place a variety of different parts – are critical for realising a highly customised production process.

Sustainability & Green/Circular/E-Waste Manufacturing

Sustainability and green manufacturing are well suited to the microfactory model.

So where are the main benefits of sustainability in a microfactory?

The first and most important element is that the microfactory is suitable for customised production, which is the opposite of mass production. This brings as advantages a lower use of raw materials and a reduced consumption of resources to make the product. In other words, it is produced on the basis of the customer's real request, and when there is genuinely a need for it.

Customised production also decreases the amount of waste generated by unsold items and the same production methods are aimed at reducing waste, to make the company economically sustainable.

The microfactory tends by its very nature to produce products that comply with the requirements of the circular economy. In some cases, the products can be more expensive than those generated by mass production and, consequently, the added value is the durability and repairability of the product.

A final aspect that makes a microfactory more sustainable is flexibility. The change in production must, in fact, be more agile to be economically sustainable. This approach leads to a saving of resources destined for production. That is, it leads to giving priority to machines that are able to produce flexibly and that are able to reduce frequent replacements.

OPPORTUNITIES AND RECOMMENDATIONS

Reducing Complexity – Main Advantages (all)

Current manufacturing practices are often unnecessarily complicated, which results in wasted materials, lack of flexibility, higher cost of production, and highly compartmentalised functions. The microfactory approach can result in significant advantages for the firm, especially if production volume is relatively small scale, and customised. Each firm should therefore consider what is most advantageous. Even very large multinational companies have relatively low volume production, which lends itself to a microfactory approach.

New Approach with Highly Skilled People

The microfactory concept differs from the traditional manufacturing concept, and thus requires a change of mindset and a new agile approach. Multidisciplinary teams with a mix of competences (from mechatronics to systems engineers to software experts) must work together in an agile way to realise the required automation tasks and modules within a very short time. Also, for the operation and supervision of the technologically advanced manufacturing setup, a few but highly skilled people are required. As microfactories are mainly located near customers, manufacturing customised products only after getting confirmed orders, the great importance of customer care and service becomes obvious.

Beyond customised production close to clients, the general microfactory concept also provides a valuable approach for modular cyber-physical learning factories as a universal platform for technical education and training, as well as for researching Industry 4.0. For example, a modular cyber-physical lab system is officially being used at the upcoming WorldSkills event in Shanghai for the brand-new 'Industry 4.0' skill competition.[7]

The Technology Opportunities

From a technological perspective, Smart Microfactories could offer the perfect production plant size and features to test and implement the latest innovations in technology.

Technological innovation applications can vary, from operational technologies, from cybersecurity tools to collaborative robots □ hat could enable real cobot manufacturing with a human-machine real-time interaction □ to a mass customisation guaranteed by 3D printing and additive manufacturing techniques. There is a wide range of technologies which makes developing microfactories challenging, often due to a lack of awareness of what is possible.[8]

One important point to keep in mind is that implementing technologies inside a smart microfactory is not the final goal, it should be the means through which the manufacturing objective can be achieved and, depending on the need, some technologies could fit better than others.

In the end, whether implementing all or only part of the former list of technologies, the real opportunities come not only from this flexibility of the smart microfactories production systems, but also from the timeliness with which they can be build up and made fully operational, while limiting the investment required.

Quantifying return on investment

Every innovation should be managed at a corporate level by trying to understand if the benefits could be much higher than the costs. So what return on investment could either managers or entrepreneurs obtain?

We have made the argument that microfactories enable implementation of production in a fast, flexible manner. This is particularly important if certain non- standard situations arise. A new pandemic, natural disasters or trade sanctions, for example, drive a shortage of certain types of goods. Microfactory production could be the answer to ensure supply continuity. In addition, microfactories could be the lever to enable the reshoring trend, moving production very close to where demand arises. In this perspective, smart microfactories would fit perfectly inside a lean process following the industrial agile philosophy.

In addition to the aforementioned benefits, it would be also possible to get a return from smart microfactories considering another two supplementary aspects: on one hand, the continuous flow of product and the eliminated need for outsourced delivery could lower the costs related to stocks (i.e., inventory costs) as well as those related to demand (i.e., stock-out costs); further, considering the higher control over the production process and the technologies that could monitor these sites, production waste could be further reduced with an improvement in performance in terms of efficiencies and sustainability indices.

Finally, for some companies, microfactories can be implemented in parallel with a more traditional production plant. The smaller type can be exploited in two ways. Running in parallel, to finalise products the two production sites would enable the management of the smart microfactory or pilot plant as an experimental lab to introduce small-scale batches and conduct training sessions, while later, the new approach could be integrated into a larger plant.

CONCLUSION

Modular microfactories can be an approach to improve the overall productivity of the manufacturing industry. As automation and digital technology continue to advance, this enables managers to consider a more self-contained approach to manufacturing for specific products.

While not a panacea for all manufacturing needs, microfactories can play an important role in the circumstances we have identified. The pandemic has shown that small, agile factory production can have an important function in meeting customer needs.

We include three case studies which describe how microfactories can efficiently and effectively produce products in several diverse industries, such as in electric vehicle production, electronics and pharmaceuticals.

ANNEX

Case Study: Local Motors

The Company

Local Motors was founded in 2007 and leverages digital manufacturing, open collaboration, co-creation, and micro-factories to produce ground mobility vehicles in a cost-effective way at small scale.

The Customer Problem and Challenge

- High manufacturing costs
- High manufacturing lead times

Managing Change and Corporate Culture: Key Aspects

Local Motors adopts co-creation and open-source collaboration to drive innovation, which significantly improves lead times, saves R&D costs, and is an effective marketing tool.

Local Motors has a culture of community. They use locally-sourced components wherever possible, and employees are upskilled and part of the local community

The Solution

Through open collaboration, crowd-sourcing, micro-factories, and additive manufacturing, Local Motors can drastically decrease manufacturing costs and lead times in their production. Without traditional vehicle production lines, these small-scale modular micro-factories are capable of flexing/iterating to different needs and technological advancements, while reducing lead times and energy use. Local Motors uses locally-sourced components and local employees to help achieve this as well, which creates jobs and educates the workers of today in the rapid advancements of the digitisation of manufacturing.

Outcomes and Achievements

At IMTS 2014, Local Motors debuted the Strati – the world's first 3D-printed electric car. The car body parts took 44 hours to print, followed by milling and assembling.

At IMTS 2018, Olli, an autonomous, electric shuttle bus was introduced. Olli is 80% 3D-printed using 100% recyclable material. Olli is being manufactured and assembled in multiple micro-factories and has been deployed across the globe.

Local Motors has built and opened two micro-factories in Arizona and Tennessee and plans to open a third in Europe.

Case Study: Pharmaceuticals

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The Customer Problem and Challenge

Continuous manufacturing has been used for decades for the production of different chemicals, for example in the oil and gas sectors. The use of continuous production of pharmaceuticals is not as developed as in the oil and gas sectors. The last 20 years have seen an increased interest in developing alternative continuous processes that can overcome previous problems in pharmaceutical applications such as small volume or more complex chemicals.

Continuous production of pharmaceutical products offers known advantages such as better process control, increased safety, easy scale-up and greener processes. Other potential benefits are the reduction of the supply chains and modularisation of supply. For these reasons, many pharmaceutical companies are interested in developing continuous processes or flow chemistry; companies may include Pfizer, Merck, Astra Zeneca, and Johnson and Johnson, among others.

3D-printed parts have been used to produce pharmaceuticals for several years and some examples include continuous stirred-tank reactors (CSTRs), an airlift crystalliser, and mixers; our group proposed a falling-film crystalliser, which integrated a 3D-printed part with traditional pipes and connectors. There are still limitations on the use of 3D-printed parts, such as chemical compatibility, pressure or complex geometries that may not be suitable for powder processing. Traditionally, the production of pharmaceuticals requires the use of several solvents that are not chemically compatible with the regular polymers used in printing processes. Many of the chemical processes also require significant pressure, so an important characteristic of 3D-printed parts for pharmaceutical applications is the ability of the part to be gas- and liquid-tight and to be able to stand moderate pressures. Finally, the printing process would not be suitable for some of the proposed designs; for example, a common requirement is to use large cavities or long tubes to increase the residence time of the reactants. The use of powders could block the tubes, or an intricate design could have a poor printed quality, decreasing the effectiveness of the part. The use of 3D-printed stainless steel, titanium or Poly(ether ether ketone) (PEEK) can help to reduce these limitations.

The Solution

Recently a mixer/reactor was developed in our group, made in PEEK, which was able to stand pressures of 60 bar. Also, a 3D-printed back pressure regulator (BPR) was developed in PEEK for inline liquid separation/purification processes. Figure 1 presents the images of the designed mixer and back pressure regulator in PEEK. These process units are very efficient for laboratory-scale operations, however scaling up still represents a significant challenge with the current capabilities in 3D-printing.

We developed a hybrid approach for the continuous/semicontinuous manufacturing of intermediates and active pharmaceutical ingredients where highly engineered parts are 3D-printed and more common geometries are kept from of-the-shelf products. This hybrid approach has the benefit of keeping the costs relatively low for a complete process equipment, but this limitation could be removed in the near future as the cost of the printed parts decreases.

Another benefit of the hybrid approach is that scale-up could be achieved by replacing off-the-shelf parts with longer/bigger parts, using the same 3D-printed parts. Larger/commercial production scales could be achieved using several units in parallel (numbering-up) if required. A falling-film solution layer crystalliser was developed in our group where a complex part was 3D-printed in stainless steel for the homogeneous distribution of the liquid. This part was connected to a pipe to cool down and crystallise the desired product. The pipe could easily be extended to increase the residence time and expand the crystallisation area of, (and recover), the desired product. The connection between the 3D-printed parts and the off-the-shelf parts was achieved using threaded endings. Figure 2 presents the images of the crystalliser and the 3D-printed part. Experiments using this crystalliser showed that it was possible to produce over 1 kg/day of the desired model drug (ibuprofen) if two units could be used in parallel. A larger production scale could easily be achieved by numbering-up without the need for time-consuming scale-up studies.

The idea of creating a modular 3D-printed microfactory for the continuous production of pharmaceuticals has been discussed for some time. However, technical difficulties have prevented the development of the process. Printing a full microfactory as a single piece would be very difficult and may require a larger printing volume than that which is available at present.

Modular interchangeable components is a more suitable idea, as smaller parts would be easier to print and scale up. Additionally, the parts could be moved to a different position in the process or interchanged with a different process unit, enabling the modification of the production process for different pharmaceutical products. This could be achieved using modular connecting blocks and valves that direct the reactant's flow to the reactors and separators. Figure 3 presents a conceptual idea of how a microfactory could look in the context of pharmaceutical applications.

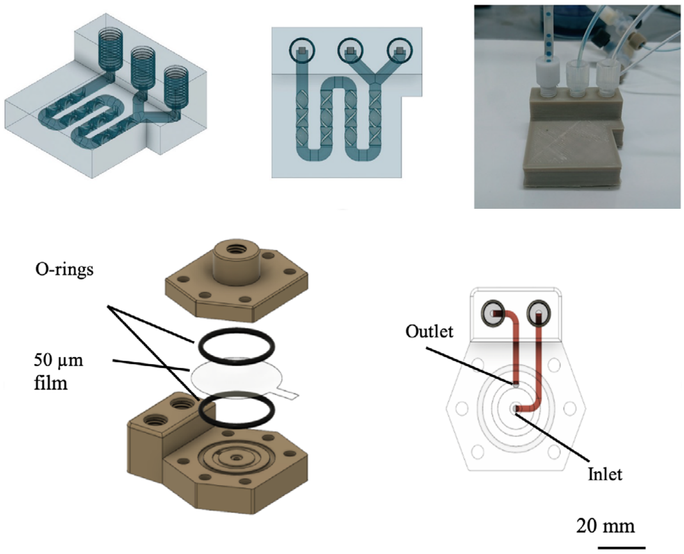
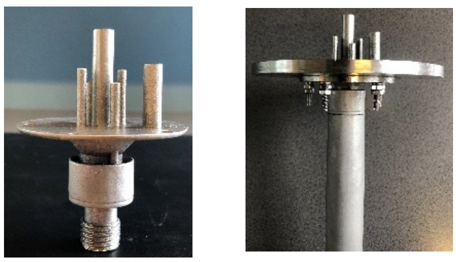


Figure 1. (Top left) CAD image for the mixer, orthographic view, (top centre) CAD image of the mixer, top view and (top right), 3D-printed mixer in PEEK. (Bottom left) CAD image showing two-part BPR construction, (bottom right) Transparent view showing the internal channels (highlighted in red). The scale bar is only for the bottom images.



Threaded ending for easy connections.

Figure 2. (Left) CAD image of the falling-film solution layer crystalliser, (centre) 3D-printed part in stainless steel and, (right), Assembling of the 3D-printed part with other off-the-shelf components.

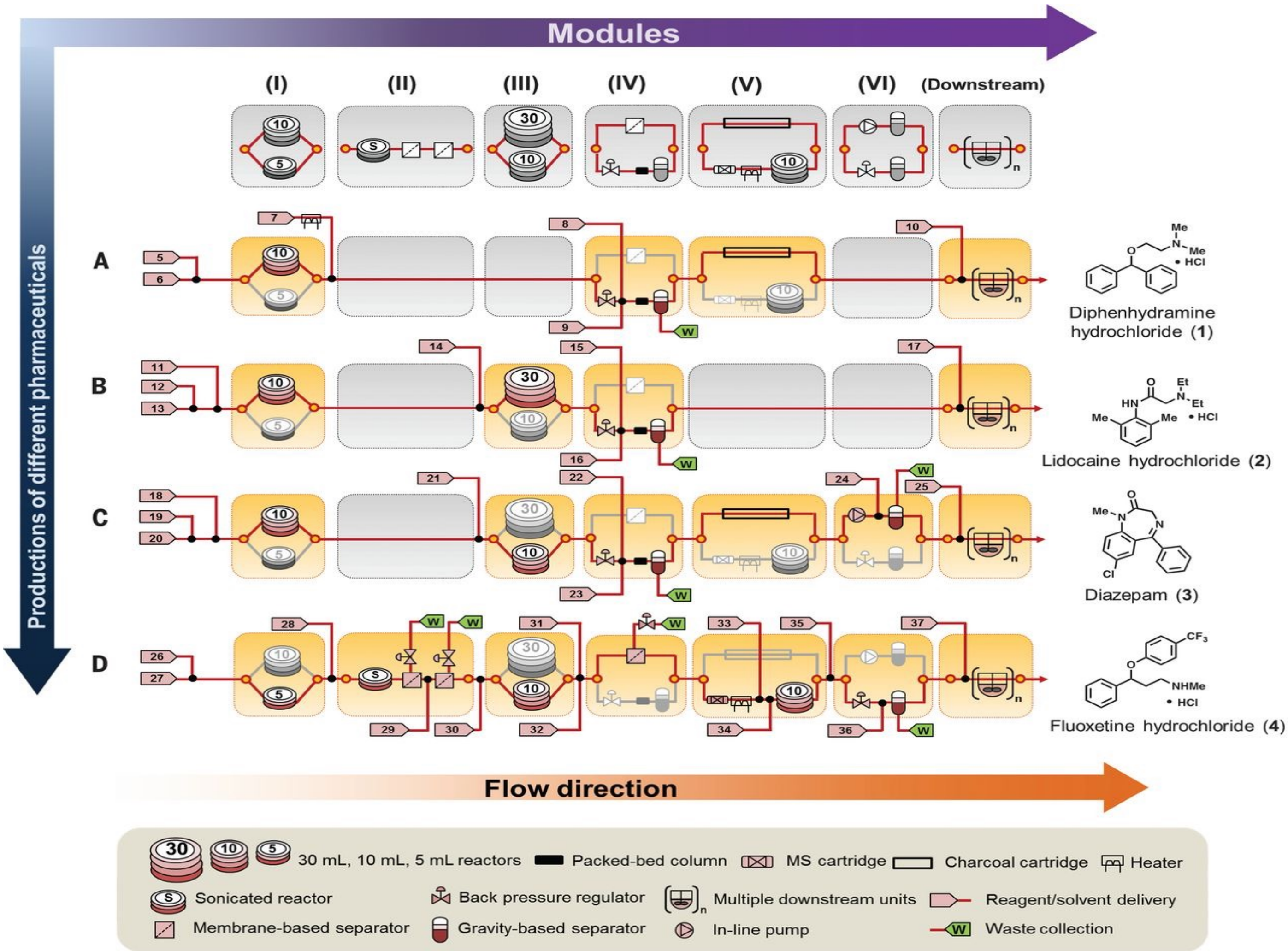


Figure 3. Conceptual design of a reconfigurable factory for the delivery of different drugs on-demand.1

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