Modular manufacturing processes: Status, challenges, and opportunities

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Modular Manufacturing Processes: Status, Challenges and Opportunities

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Abstract

Chemical companies are constantly seeking new, high-margin growth opportunities, the majority of which lie in high-grade, specialty chemicals, rather than in the bulk sector. In order to realize these opportunities, manufacturers are increasingly considering decentralized, flexible production facilities: large-scale production units are uneconomical for innovative products with a short lifespan and volatile markets. Small modular plants have low financial risks, are flexible and can respond rapidly to changes in demand. Logistics costs can be also reduced by moving production closer to customers and/or sources of raw materials. Moreover, stricter safety regulations can in many cases be more easily met using smaller distributed facilities.

Modularization of chemical production can thus have potentially significant economic and safety benefits. In this article, we review several drivers for modular production, and evaluate modular production architectures based on the value density of feedstock resources and markets for the products of a process. We also discuss the links between modularization and process intensification. We illustrate the discussion with an array of industrial examples, which we also use to motivate a summary of challenges and future directions for this area.

1 Introduction

For nearly a century, the discipline that we proudly refer to as "modern chemical engineering" has been defined and driven by two fundamental tenets. First, the *economy of scale*, which dictates that making chemical plants larger will make their construction more capital-efficient and improve the utilization of resources, thereby reducing the operating cost and the price of products (while improving profit). Second, these plants are designed and built using a relatively uniform set of building blocks, i.e., *unit operations*. Following the vision of pioneer Warren K. Lewis, the unit operations framework afforded method and structure to the synthesis and analysis of chemical plants, and provided a rational and systematic path towards performing (shortcut) process design calculations in an era ruled by the slide rule rather than by the digital computer. This has in effect perpetuated in the way chemical engineers design, simulate, optimize (and teach) process designs today.

These tenets have not, however, remained without challenge. *Process intensification*, a concept hinted at by some early results in the first part of the twentieth century[1], and augmented over the past two decades, aims to alter the conventional "one unit–one operation" approach by combining multiple unit

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operations in the same physical device. By bringing multiple physical and chemical processes in close physical proximity, intensified systems minimize transfer/transport limitations. In turn, this means that phenomena such as catalytic reactions are governed by their intrinsic rates, rather than by diffusion through the catalyst structure. As a consequence, such intensified devices tend to be smaller and more efficient than their conventional, unit-operation counterparts. Moreover, reduced dimensions have safety advantages, lowering the holdup of potentially harmful chemicals and reducing the process response time for process control.

The choice of physical dimensions often plays an important role in the conception and construction of intensified systems. Indeed, such systems are only viable at certain length scales. While, for example, dividing wall columns appear to be quite scalable in capacity, the channel height of microchannel reactors cannot exceed a few millimeters lest homogeneous reactions (notably combustion) start to occur. In turn, this places limitations on the processing capacity of some intensified processes, and it has been argued that increasing throughput should be achieved by "numbering up" (i.e., increasing the number of devices operating in parallel)[1].

Numbering up is an indirect challenge to the first tenet mentioned above, of the economies of scale. Conventional scale-up techniques increase capacity over an existing system by designing and constructing a device/process that is conceptually similar in functionality but of (significantly) larger size. In this manner, the plant capacity can be chosen from a continuous range, with the optimal value driven by a typical tradeoff between market capacity, capital expenditure and operating cost. On the other hand, numbering up only affords discrete choices in setting the capacity of a plant, by selecting the (integer) number of (typically identical) processing devices/modules. The product portfolio of a facility can also be expanded by adding the relevant modules.

While not nearly as widespread as in other sectors (e.g., electronics, automotive), modularity has been present in different forms in the process industries for at least half a century, and the intent of this paper is to review the status modular manufacturing developments, analyze their role in today's chemical industry and identify challenges and opportunities that should guide further developments in the area.

We categorize resources and markets in terms of a newly defined metric, *value density*, and argue that the opportunities for modular manufacturing are tied to this metric. Moreover, we posit that process intensification is an enabler but not a necessary condition for modular manufacturing.

2 What is "modular?"

The dictionary [†] defines a module as "any in a series of standardized units for use together." For many a reader, this will immediately bring to mind –and not without justification– the aforementioned unit operations framework. Indeed, unit operations are modules in their own right, as they have been deliberately standardized to work together from a functional perspective. However, in this article we do not intend to refer exclusively to unit operations as the modules of interest. To the contrary, our intention is to look beyond the conventional unit operations framework. More specifically, modularity based on process intensification goes beyond the unit operations by allowing the synergistic combination of fundamental functions (tasks) into a single equipment (e.g. reactive distillation, spinning disk reactors, membrane distillation, heat-integrated reactors or distillation columns). While both PI techniques and modular manufacturing can used independently, it is more beneficial to apply first PI to various sections of a process and then combine the PI solutions as modules for the overall plant.

Thus, in the context of chemical processing, we identify three categories of modularity: *modular fabrication and construction*, *modular design* and *modular manufacturing.*

Modular fabrication and construction

Modular fabrication and construction is probably the oldest attempt at modularization of chemical plants, going back to at least the 1960s[2]. Modular fabrication and construction denotes the situation where a single facility of annual capacity P is built from (not necessarily identical) factory-preassembled blocks/modules, that are interconnected in the field with minimal effort, as opposed to a largely field-erected (also referred

[†]http://www.merriam-webster.com/dictionary/module, last retrieved 10/17/2016

Figure 1: A shipping container-sized module consisting of two heat exchangers. The top of the module serves as a pipe rack. Photo used from permission from Mr. Bill Stanley.

to as "stick-built") structure. Such modules may comprise one conventional unit operation, several unit operations or only part of a unit operation.

Process design for modular fabrication and construction ensures that the functionality of the process is exactly the same as in the case of a conventional facility[2]. The module is typically piped and all tubing, wiring and control connections are complete. The module communicates with the rest of the plant (i.e., other modules) by containing junction boxes for power wiring and control wiring and a header for instrument air. In many cases, the pipe rack is integrated in the module, with the top portion of the module carrying the aforementioned ducts and piping (Figure 1).

The detailed engineering and mechanical design of each module should account for considerations such as module weight and dimensions (driven by transportation constraints and the size of the plot of land available for plant installation), strength of frame materials (to support the weight of the equipment within the module, as well as to withstand any conditions encountered during transportation), the need for an foundation for the module to be deployed, etc.

There are several advantages to modular construction, which outweigh a potential (or perceived) increase in upfront cost[3,4,5,6,7]:

- Factory assembly provides greater quality control and increased worker safety: shop personnel operate in a facility with a controlled flow and with access to overhead cranes: for example, most of the welding on a distillation tower can be carried out with the column in the horizontal position, thereby avoiding elevated work. Workers remain in a small area with the work brought to their workstation, and they are more aware of their surroundings and the location of all inputs (tools, industrial gasses, electrical supply points, etc.) needed to perform their job. Usually, they also know their coworkers and develop a working relationship promoting safety and efficiency. By contrast, a field worker moves around the construction site to the required work and must move all required equipment. Elevated work on scaffolds and the use of mobile cranes are typical, with the inherent increase in safety risks. Personnel are subject to inclement weather. Frequently, teams are assembled for each job and there is minimal workforce cohesion, unlike a fabrication shop with consistent staffing.

- Capital cost savings, largely due to labor efficiency. In the authors' experience, a large portion of the capital costs for a project is welding. A welding worker working in a shop is considerably more efficient than the welder in the field. As mentioned above, the shop welder remains in the same location and is welding a high percentage of his time, whereas a field welder is less efficient. In 2016 in the Houston area, a productive hour (one weld on a 6 inch schedule 40 carbon steel pipe) for a welder cost about $50 (including all overhead items). The cost for field work is almost always at least twice that of shop fabrication and could increase up to a factor of 6, depending on the skill level and availability of the relevant work force.

  Savings in the cost of materials are also possible. While the modules may require some extra steel, the cost is offset by saving on the cost of foundations, the majority of which can be avoided. Further savings come from reducing the amount of piping required at the plant level, with pipe racks built into the modules themselves.

- Savings on deployment cost and project timeline: assembling the modules requires far fewer man-hours of skilled labor than building the plant in the field, shortening project execution times (Figure 2). The amount of work that can be carried out in the shop (via modular construction) relative to the amount of work to be completed in the field varies from project to project, but shifting the majority of the work towards the shop can have significant benefits in places where qualified labor and expertise may be in very short supply.

In the authors' experience, in a typical modular construction refinery project, about 65% of the labor is performed in the shop instead of the field. Considering the labor savings and the economics from the initial stages, the total cost of a project can be reduced by an order of about 30%. Time savings are a considerable contributor: on a three-year project, approximately one year can be saved on the project utilizing extensive modularization, leading to an early startup, lower overhead costs and the financing for the project reduced by one year.

One of the challenges to be taken into account when considering a modular construction approach is transportation: as module size increases, so do the logistic difficulties of delivering it to the plant site. Further, modules may require a higher amount of upfront engineering than conventional unit operations, and a very detailed design package must typically be available when modules are ordered from external fabricators[7].

The literature provides numerous examples of modular construction, including catalytic cracking units[8], steam methane reformers[3], landfill gas processing plants[8], petrochemical facilities[8], chlor-alkali plants[9].

In the authors' experience, modular construction can be applied to any type of plant, or at least parts thereof, with the main limitation being the logistics of shipping the modules: rail or road transportation typically limit the size of a module to that of a standardized shipping container - see Figures 1 and 3. This further places a practical upper limit on the capacity of a plant that can be deployed via modular construction; for example, oil refineries can be constructed with such modules up to a capacity of about 30,000 barrels/day. Access to a sea or river port allows for modules of larger size.

Modular design

We use the term *modular design* to designate a situation whereby a production facility of annual capacity P is designed for and built with pre-specified, standardized building blocks ("modules"). This can include off-the-shelf reaction vessels, heat exchangers, separation units, etc. These modules (based on unit operations or novel process intensification techniques) can also feature standardized interconnections for fluid flow, information, data and control signal exchange, and utility connections[10]. Modular design can reduce engineering costs considerably, but at the cost of diminished flexibility[11].

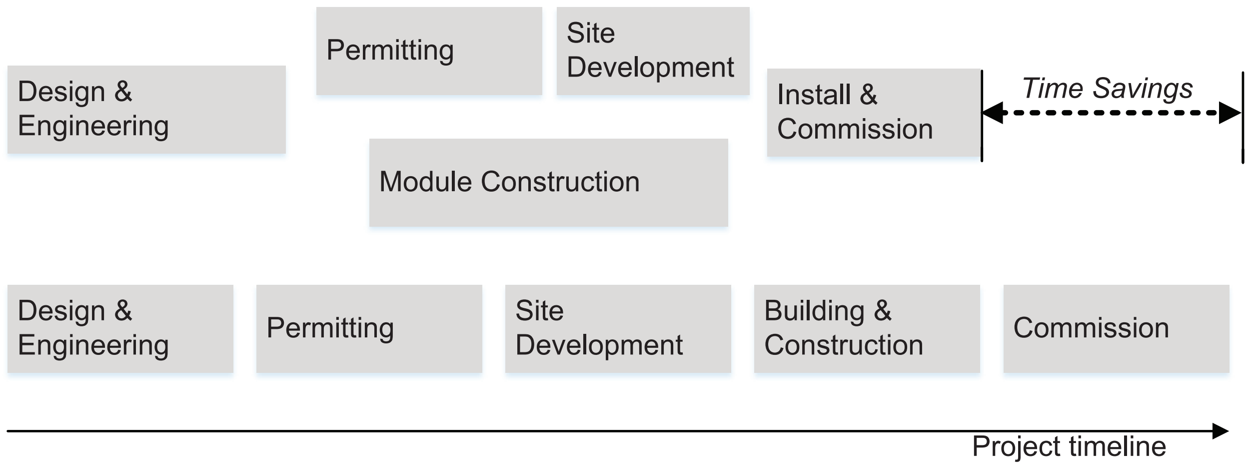

Figure 2: Execution timeline for conventional (bottom) and modular construction (top) projects

Figure 3: Modularized distillation system includes boiler, fractionator, overhead condenser, heat exchangers, pumps and controls. Photo used with permission from Mr. Bill Stanley.

Modular deployment and production

We refer to *modular production* as the situation where n similar or identical facilities (modules), each of capacity P/n, are used to meet processing capacity P. These facilities are typically operating in parallel, may or may not be deployed at the same time (meaning that capacity can be expanded or reduced over time) and may or may not be geographically co-located. The facilities can themselves be of modular fabrication and construction (a facility may in effect consist of a single fabricated module), and can benefit from process intensification (PI). However, a careful balance must be kept between the degree of integration and intensification, and the need for ensuring the controlability and operability of the process.

Modular deployment and production represents a more recent effort in modular manufacturing, and has been motivated by the need for more flexible (in terms of capacity, product type and geographic location) production. A modular facility of this type typically comprises a "backbone" module that provides utilities to and connectivity between the "production" modules[12]. Modular deployment and production provides several advantages compared to a conventional facility with fixed capacity P[13,14,15]:

1. faster time to market: assuming that a module for producing the desired product is available (either as a complete construction blueprint or already constructed), it could be deployed in very short time to meet an immediate product demand. Modular deployment is thus well suited to production of novel products or for entering emerging markets. Even for new plants, shorter schedules are possible (with time savings of up to 40% and early profit) as the module construction can be carried out in parallel to the site construction, or while waiting for permits.

2. lower costs: 30% energy savings, 20% lower operating costs and 40% less capital expenditure are possible. Reducing the size of field crews, more efficient use of materials and shorter schedules all lead to capital expenditure savings. Plant operation can start (or continue) as new modules are built and commissioned.

3. scalable capacity: capacity can be scaled in time as market size evolves by adding or removing modules – an additional feature that supports the use of modular deployment for new products or emerging/developing markets, where demand is expected to grow (or fluctuate) over time. The ability to add (or remove) production capacity over time (combined with the possibility of diversifying the product portfolio by adding *different* modules – either continuous or batch) also represents a means for dealing with market uncertainty throughout the lifetime of a plant, potentially simplifying or facilitating business and investment decisions[16,15].

4. simplified maintenance and lower downtime: in order to minimize the time that a production facility is off-line due to breakdowns or routine maintenance, a module could be simply replaced with an operable one or one whose maintenance is up-to-date. The replaced module can then be serviced on-site or transported off-site for service in a central, specialized shop. Naturally, the cost of a replacement module can be significantly higher than the cost of the spare part that is actually needed for repairs in case of a break-down[9].

5. superior safety: modules can be tested at the manufacturer's facility prior to shipping to the production site. Safety risks are reduced as the modules are built under controlled conditions as discussed above.

6. single-source responsibility: building modular units in a dedicated workshop allows the project team to act as a single-source supplier of equipment and services: detailed engineering, project management, fabrication of equipment, modular assembly, insulation, automation and control, startup assistance, operator training, services and advice. The industrial suppliers include among others: CB&I, Zeton, Koch Modular Process Systems (KMPS), FB Group, MTSA Technopower, Fluor Corp.

When to choose modular deployment and production?

The primary factor that determines the choice of a modular deployment production system (instead of a conventional process of equal capacity) is economics. We analyze the economics of modular production by first considering a centralized modular facility, and then focusing on distributed modular production, whereby the modules are placed at different locations to account for distributed resource availability or a geographic spread in market demand.

Centralized modular deployment

Consider the well established "power law" cost scaling estimate[17] for a conventional process of capacity P:

$$C_c = (k_c P)^{e_c} \tag{1}$$

where C is cost, k and e are parameters, with $k > 0$ and $0 < e < 1$ (typically $e \approx 2/3$), and the subscript c denotes a conventional process. We assume that this relation holds for the entire range of capacities, for both scale-up and scale-down, i.e., from P/n to P. Hence, the cost of a facility of capacity P/n (i.e., a module) will be

$$C_m = \left(k_c \frac{P}{n}\right)^{e_c} = \frac{1}{n^{e_c}}(k_c P)^{e_c} \tag{2}$$

where the subscript m stands for modular. Since $n \geq 2$ and $0 < e_c < 1$, clearly $n^{e_c} < n$ and hence $\frac{1}{n^{e_c}} > \frac{1}{n}$, the cost of one module (out of n) is expected to be higher than $1/n$ of the cost of a conventional process. Equivalently, a modular centralized plant of capacity P will be more expensive (from a capital point of view) than a conventional plant of equivalent capacity.

We note that this comparison is based on two premises (see also[18]):

- P1: the market conditions for the modular and conventional processes are similar
- P2: the two processes utilize the same technology, and an efficiency penalty is possibly incurred for scale-down

We note that, in fact, it is possible possible that the cost of the nth module may be lower than the cost of the first owing to a "learning" effect (i.e., learning, over time, potential ways to decrease the cost of making a module)[19] and due to natural economies of making the modules in larger numbers. Further, as mentioned above, not all modules have to be deployed immediately; rather, modular capacity can be increased as market demand grows. Finally, numerous examples of modularly deployed plants[12] make use of innovative technologies and process intensification (i.e., they do not use the same technology as a conventional plant) to further lower the cost of a module. All these factors contribute to lowering the capital cost of a centralized modular facility, and, conversely, bringing its net present value (NPV) more in line with that of a conventional plant.

Extensive empirical evidence collected during the industry-academia "Flexible, Fast and Future Production Processes" collaborative project sponsored by the European Union (the "F^3 Factory")[12] suggests that modular deployment and production lend themselves well to high-value (more than 100 euro/kg) products made in low-to-medium volumes, and potentially in geographically distributed facilities. Lier and Grünewald[19] (who considered a very specific case study) found that the NPV of a modularly deployed plant is lower than the NPV of a conventional facility when consider a longer (> 10 years) time horizon, further suggesting that modular production is suited to meeting short- to medium-term market needs that also fluctuate in time.

In our estimates, we admittedly exclude the cost of labor. Paradoxically, this cost scales relatively well at both ends of the spectrum[18]. Due to advances in technology, the personnel required to operate a very large scale facility is likely not much larger than the number of operators involved in running a plant of comparably smaller size. Similarly, modular production plants can be operated remotely, with a single, minimally staffed control center providing oversight for multiple such facilities.

The arguments above suggest that the decision to select a centralized modular facility should be based on a careful analysis of both capital cost and market evolution prospects. A description of a software that enables a detailed evaluation of modular production concepts is provided by Sievers et al.[20], while a specific example is discussed by Lier and Grünewald[19].

Geographically distributed modular deployment

In what follows, we provide a new perspective on the economics of distributed production using modularly deployed plants. We define the annual benefit of a conventional centralized process as a function of operating cost and the capital cost introduced above, as:

$$B_c = \pi_p P - [(\pi_a + \pi_l)P + \alpha(k_c P)^{e_c}] \tag{3}$$

where π_a defines the unit acquisition price of feedstock and π_l are the corresponding logistic costs. α represents a capital cost coefficient and π_p is the product unit price (including the logistic costs for the product).

For simplicity, we and assume that:

- the acquisition price remains relatively constant
- the logistic costs can be decreased by appropriately locating the processing modules (see, e.g., Lara and Grossmann [21]), and decrease linearly with the number of modules
- the logistic cost for the product is small compared to the logistic cost of the feedstock (similar arguments can easily be made in the reverse scenario, whereby the logistic cost of the feedstock is small compared to the product).

The annualized benefit B_m for the corresponding modular processing facility is:

$$B_m = \pi_p \beta P - \left[\left(\pi_a + \frac{\pi_l}{n} \right) P + \alpha n \frac{1}{n^{e_c}} (k_c P)^{e_c} \right] \tag{4}$$

where $0 < \beta \leq 1$ accounts for potential yield and/or efficiency losses owing to scale-down of a technology.

Then, we compute the difference between the annual benefit of the distributed modular and centralized conventional processes as:

$$B_m - B_c \quad = \quad \pi_p P(\beta - 1) + \pi_l P \left(1 - \frac{1}{n} \right) + \alpha (k_c P)^{e_c} \left(1 - \frac{n}{n^{e_c}} \right) \tag{5}$$

We analyze the difference term by term as follows:

- the first term reflects the yield and/or efficiency loss due to modularization and is at most zero, showing that modularization likely incurs an efficiency penalty
- the second term corresponds to logistics costs, and will always be positive, showing that under our assumptions modular production is superior to a conventional process in terms of logistics
- the third term corresponds to the capital cost and will always be negative, indicating that modular processes remain inferior to conventional ones from a the point of view of capital expenditure for the same technology.

Thus, equation (5) provides guidance for selecting between distributed modular and centralized conventional production based on the desired production capacity, the number of modular production units, the cost scaling model and the desired payback time. A conventional process of capacity P is viable when feedstock is available at a rate corresponding to P without incurring considerable logistic costs (recall that here we assume that the logistic cost of the product is small), and distributed modular manufacturing is preferred otherwise (assuming that the technology itself is cost-competitive at the relevant scale, or that a different but cost-competitive technology exists at this scale).

These arguments further suggest that the potential of a geographic area for supporting a conventional centralized or modular distributed or decentralized production strategy can be assessed in terms of a *value density* Ψ which we define based on a desired annual production capacity P:

$$\Psi = \frac{\pi_p}{\pi_l} \frac{D_{resource}}{P} \tag{6}$$

where $D_{resource}$ captures the physical density of a resource in terms of available annual supply rate per unit area.

The value density Ψ can be interpreted as follows:

- *low* (sub-unitary) values point to either, i) a low $\frac{\pi_p}{\pi_l}$ ratio, suggesting high logistic costs compared to the price of the product, ii) a low $\frac{D_{resource}}{P}$ ratio, suggesting that the area may not be capable of supplying sufficient feedstock for the desired capacity, or, iii) both.

- *high* (supra-unitary) values conversely indicate that logistic costs may be low, and/or the feedstock in the area is abundant

The value density can thus be used as a criterion for selecting between distributed, modular and conventional, centralized production, with high value densities indicating that centralized production may be appropriate, while a low value density favoring the choice of modular production (Table 1). We note that value density is intended as a screening criterion, and the decision to invest in a distributed/modular or centralized process (particularly at intermediary values of Ψ) should be made by taking in consideration the cost and efficiency of the process as described above, as well as predictions regarding changes in market demand and feedstock availability. Intermediary values can also be used to perform an objective comparison of business opportunities related to similar circumstances (e.g., invest in distributed manufacturing in area A or in neighboring area B?).

Table 1: Value density scenarios

$\frac{\pi_p}{\pi_l}$	$\frac{D_{resource}}{P}$	Ψ	Comments
low	low	low	modular deployment and production
low	high	intermediary	high logistics cost, should undertake further analysis
high	low	intermediary	area will not support production
high	high	high	conventional centralized production

As an illustrative example, we consider the production of atmospheric gases (particularly, nitrogen and oxygen) and hydrogen, which are used to support numerous manufacturing and fabrication processes. Gas demand can often be satisfied by delivering gases packaged in cylinders. For higher demands, the corresponding liquefied products can be delivered via tanker trucks and stored on-site in cryogenic tanks. For still higher demand, deliveries become uneconomical, and small-scale on-site production is possible[22]. For example, Praxair, Inc. of Danbury, CT[23] offers small on-site air separation modules that can produce nitrogen (via cryogenic separation) at rates of up to 5,000 Nm^3/h. Likewise, oxygen of up to about 95% purity can be generated via vacuum pressure swing adsorption at rates of about 6,000 Nm^3/h. Air Products and Chemicals (Allentown, PA)[24] offers skid-mounted, modular hydrogen generators that rely on steam reforming to generate up to 5,000 Nm^3/h. We note that these quantities are very small compared with the production rates of "world class" plants (which can reach (or exceed), e.g., 90,000 Nm^3/h for oxygen and 112,000 Nm^3/h for hydrogen (100 million standard cubic feet per day), and reflect the low value density (as far as small-to-medium scale users are concerned) of the industrial gas market. It is noteworthy that, in addition to economic benefits, on-site production eliminates the safety hazards associated with the transportation of cryogenic liquids and highly flammable hydrogen.

Another example of developing distributed, modular production plants pertains to the production of hydrocarbon liquids using stranded natural gas feedstock. Natural gas deposits are referred to as "stranded" when their small scale and/or remote location render their exploitation and monetization via conventional means (i.e., building a pipeline to consumers), economically infeasible. It is currently estimated that one third of natural gas resources worldwide belong to this category[25]. Stranded natural gas is thus a *resource* with low value density (rather than a low-value density market as in the previous example), and its processing calls for a distributed approach. Indeed, several authors[26,27,28,29] have advocated the development of small-scale gas to liquids (GTL) processes, which convert stranded gas feedstock into more fungible and more energy dense liquids, typically via steam-methane reforming followed by Fischer-Tropsch synthesis, confirming the relevance and applicability of modular production in this case. Commercial deployments have also been reported, with capacities reaching 1000 barrels per day[30]. It is noteworthy that the neither steam-methane reforming nor Fischer-Tropsch synthesis reactors scale down favorably, and process intensification (in this case, in the guise of catalytic plate/ microchannel reactors) has played a key role in making such systems economically viable.

Similar arguments can be applied when considering distributed biomass processing. Biological feedstock is cultivated on fields (e.g., switchgrass, sorghum, corn and corn stover) or harvested from aqueous environments (e.g., algae); owing to the geographically distributed nature of its production, biomass is a low value density resource, and hence biomass conversion to fuels and/or chemicals is well suited to modular (pre)processing. This has indeed been prominently advocated in the literature[31,32,13], with the processing pathways geared towards the production of platform chemicals or transportation fuels. With the exception of the well-developed ethanol production process[33], the latter rely on Fischer-Tropsch synthesis (as in the case of natural gas to liquids), with the key difference that synthesis gas is obtained via gasification. Here, too, process intensification via novel reactor technologies is playing a key role. Further biomass-based applications include power generation, and a review of progress in the field of small, modular facilities for power generation from biomass is provided by Dong et al.[34].

3 Safety and Sustainability Considerations of Distributed Modular Production

Safety is of paramount importance in the operation of chemical processes, and distributed modular deployment of chemical production has several potential advantages from this point of view. First, it inherently reduces the amount of any hazardous chemicals that may be present at a given manufacturing location. Additionally, certain chemicals can be manufactured on-site, thereby eliminating the need for transportation of hazardous materials by road or rail.

For example, onsite production of chlorine and chlorine-based oxidants has become interesting as environmental regulations (and the corresponding requirements for on-site wastewater treatment) have become more stringent. Small, modular onsite sodium hypochlorite generators are now available commercially, eliminating the need for chlorine deliveries for water treatment plants. Such generators are available in capacities of up to over one metric ton of chlorine per day from manufacturers such as MIOX[35] (Albuquerque, NM), EVOQUA[36] (Warrendale, PA) and De Nora[37] (Sugar Land, TX). Larger-scale plants (up to 15,000 tons per year), comprising multiple such modules, have been developed as well[38]. The value density of the market for on-site wastewater treatment at facilities such as resorts, hotels, etc. is inherently low, and production thus lends itself naturally to a distributed modular paradigm. Furthermore, as in the case of atmospheric cases and hydrogen, on-site production of hazardous chemicals such as chlorine presents significant health and environmental safety benefits, including eliminating the need for road or rail distribution (which can be disrupted by accidents or subjected to deliberate attacks[39]), reducing the amount of stored hazardous materials and eliminating large-scale facilities and distribution centers that may stockpile chlorine in large quantities. We note that similar arguments have been brought recently in favor of distributed, small-scale production of ammonia[40].

There are, however, tradeoffs for these benefits: the cost of containment systems is likely to scale in the same manner as the capital cost of equipment (discussed above), and thus the overall cost of such systems may be higher for a suite of modular facilities that for a conventional, centralized plant. Moreover, the disadvantage associated with storing a larger amount of potentially hazardous chemicals in a single location (in the centralized case) may be offset by the fact that the hazard is can be monitored, managed and –if needed– mitigated in one place.

Sustainability is also key in the development of new processes. Sustainability and life cycle analysis tools developed for conventional process systems (see, e.g., Allen and Shonnard[41] and Jacquemin et al.[42]) can serve as the basis for the "cradle-to-grave" design and analysis of modular processes; several additional features should be accounted for:

- modules may be depoloyed in different geographies (e.g., across U.S. state borders or perhaps across international borders) and thus subject to different safety, health and environmental regulations; in this case, the modular paradigm would suggest designing to meet the most stringent specifications, in spite of the inherent penalty incurred when deploying a module in a location where regulations are more lax

- as with conventional processes, system maintenance should be carried out regularly to ensure that all modules are tested and serviced regularly for safe and efficient operation. In the case of distributed production, this may require additional effort for coordinating the activity and travel schedules of support technicians and engineers

- modular processing offers the possibility of a staged decommissioning at the end of the service life of the process; that is, some of the modules in a plant can be decommissioned, while others continue to operate if permissible and economically advantageous (note that this consideration applies to a centralized modular facility as well).

4 Process systems engineering for modular production: challenges and opportunities

4.1 Modular process design

The cost calculations for a process module used in Equation 2 rely on the assumption that the module uses the same technology as the full-scale, conventional process. This inevitably leads to an increase in the total cost of a modular process. Process design should therefore consider new process configurations that are customized to smaller scales or that scale-*down* favorably, thereby challenging and eliminating the "same technology" assumption.

Process intensification should figure prominently in these efforts, providing new avenues for reducing module size, reducing cost and potentially increasing efficiency. Although modular manufacturing is already practiced by industry (e.g. using smaller conventional unit operations) the integration of process intensification technologies could allow major steps forward by further reducing the overall costs (e.g. fewer equipment pieces and lower operating costs) and improving safety (e.g. smaller holdup minimizing the inventory of hazardous materials).

A discussion of the interaction between modularity and intensification from an industrial perspective is given by Bieringer et al.[43]. To this end, significant progress is required from the process modeling and optimization perspective. Practically none of the commercial process modeling and design optimization software tools available today have the capability of representing intensified and modular systems explicitly and at the relevant level of detail. In order to identify the optimal design of such processes, the structure and performance of intensified setups such as autothermal reactors, jet-loop reactors (and several other devices deployed in recent modular designs[12]) must be captured explicitly. Of particular import is capturing the geometric dimensions and features, which are often at the origin of the favorable performance of these devices (high *internal* area to volume ratio is oft cited as one of the main performance-enhancing characteristics of a autothermal reactors[1]). Conversely, reduced dimensions can amplify the impact of phenomena that are routinely encountered in conventional unit operations; as an example, reducing dimensions also increase the *external* area to volume ratio, and the effect that ambient heat losses may have on an intensified autothermal reactor may be (relatively speaking) much stronger that in the case of a conventional large-scale reactor. Similar considerations apply to distillation systems (contrast, e.g., Figures 3 and 4).

Further motivation towards increasing the level of equipment geometric and constructive detail in the flowsheet modeling and design optimization stems from the need to identify opportunities for modularization at the design stage. The availability of such information provides the opportunity to optimize a plant design to fit in a specific footprint, such as that of the shipping container frequently used to package and deploy such modular plants.

A tighter collaboration between process designers and equipment manufacturers should also be established, with the aim of finding the design solutions that lead not only to high performance from a process point of view, but also to lower equipment capital costs and more deployable plants. Reducing the cost of modular equipment inherently reduces the business risk of deploying such solutions, and can therefore provide significant impetus for their adoption. Steps in this direction can conceivably include standardizing a significant number of components *within* each module (e.g., using the same type of valve wherever possible), identifying low-cost, high quality fabrication options (e.g., robot-assisted vs. manual welding), streamlining the parts supply chain by engaging suppliers, modularizing construction, choosing materials of the appropriate strength for frames, etc.

Figure 4: Modularized distillation system with heated insulated enclosure designed for low-temperature (-150°F, 172 K) service (Compare with system in Figure 3, which was designed for service in ambient conditions up to 150°F, 339 K). Image used with permission from Mr. Bill Stanley. Image obtained by merging two separate photographs and adjusting contrast. These edits do not alter the representation of the physical system).

4.2 Modular process control

It is likely that the control of modular production architectures will require expanding or modifying the set of control decisions typically implemented in process systems, where a supervisory controller meets plant-wide control objectives by directing the operation of a regulatory control layer, while the setpoints of the supervisory control system are dictated by an optimization calculation that considers production scheduling and/or real time optimization of the process state[44].

Specifically, a close coordination between production modules is required. This is especially true for parallel configurations, where a coordinating controller ensures that all the feedstock molecules are processed in the same way. Cooperative control strategies will likely be necessary to orchestrate module operation[45] in spatially distributed configurations. Furthermore, production turn-up and turn-down in the case of modular manufacturing is likely to involve activating and deactivating (turning on and off) one or several modules – a set of discrete decisions that should be accommodated in the control, coordination and cooperation mechanisms. In circumstances where the operating conditions of the system change rapidly, close coordination between process control and production scheduling will be required[46].

The development of specific architectures, such as Decentralized Intelligence for Modular Applications (DIMA) are being developed under the aegis of the Industry 4.0 initiative in Europe[47]. Future work for attaining the plug & produce capability required to create flexible, cost-efficient modules include includes the development of scalable, composable dynamic process models for model-based control. Such models could be developed by the manufacturers of the modules themselves, and delivered together with the physical module to the user in a very cost effective manner. In this way, every module would be accompanied by a "digital twin," that is used for advanced control and operational optimization.

The fact that in many cases modular plants are operated remotely without on-site personnel provides a strong motivation for further developments in process monitoring and fault diagnosis techniques. Advances in predictive equipment condition monitoring and predictive maintenance also become particularly valuable in this context.

We note here that the control of modular systems that rely on process intensification concepts may pose special challenges, related to the loss of control degrees of freedom and strong interactions between multiple phenomena[48,49,50].

4.3 Modular process operations

The discussion presented above suggests that the planning and scheduling of production, as well as supply chain analysis and optimization, play a key role in modular production, particularly in the distributed case. Modularly deployable facilities have the potential to support new processing paradigms. Among others, it is conceivable that plants can be deployed on demand to meet a stringent need (e.g., water purification or the production of pharmaceutics or supplies during a crisis), or relocated frequently as the supply fluctuates (such as following the harvest of, e.g., biomass crops in a seasonal migration pattern). Additional approaches, such as co-operative use of a facility by multiple users/co-owners or "crowdsourcing" patterns in which the resource is allocated ad-hoc at a variable cost and based on need, may emerge.

Further efforts should be expended in both process design and the optimization of process operations (in particular, capacity planning) on identifying opportunities for taking advantage of multiple, co-located distributed resources in distributed modular processing configurations. For example, several stranded gas deposits in Texas are located in areas with high potential for wind-power generation, suggesting the possibility for electricity-powered modular processing and GTL conversion[51]. Also, reverse osmosis-based desalination plants can be constructed at small scales and operated in a grid-independent fashion by using, e.g., wind power[52].

5 Conclusions

In this paper, we discuss the current status of modularization in the chemical industry and show by relevant examples that major opportunities exist for the decentralized, scalable and flexible production using modular systems. We make the distinction between modular construction of a facility and modular processing, focusing on architectures and configurations for the latter. We argue the case for modular processing in terms of the new concept of value density, a metric defined to characterize the geographic distribution of feedstock and/or markets for absorbing products.

Numerous examples show that modular processing is a concept that is accepted by many practitioners. However, the authors' experience is that the benefits of modularization (and, in particular, modular construction) are not yet universally known and appreciated. As a consequence, promoting these concepts via *training and education*, and *finding new application domains or new directions within existing ones* remain crucial for expanding the modular production paradigm.

Process intensification can and will play an important role in the expansion of modular processing by providing new process designs with favorable scale-down characteristics. Major opportunities exist to make chemical processes more profitable and sustainable through PI and other means (such as modularization), by reducing the energy use and the associated CO2 emissions, the cost of production, the amount of waste and environmental impact. Modular deployment and production can lead to increased flexibility in meeting market and customer demands. Developments in modular systems design and integration are and will be powered by advanced process intensification methods. However, intensification is neither a necessary nor a sufficient condition for process modularization.

Interactions between chemical engineers and equipment manufacturers can also lead to new equipment construction techniques that can lower capital cost without compromising performance. The convergence of these factors will likely *democratize access* to chemical manufacturing to a broader base of enterprises, particularly small businesses or businesses in developing countries. Modularization in all its guises can simplify engineering, increase plant efficiency and production flexibility, reduce the time to market, and improve the overall competitiveness.

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