Efficient Production of Specialized Polymers with Highly Flexible Small-Scale Plants

Shortened product life cycles and increased demand for specialized products lead to more challenges in efficiently satisfying customer needs. Customer demands are increasingly uncertain in terms of type, location, and volume. As a result, more flexible chemical production plants are required. Modular small-scale plants can be installed in transportation containers and, therefore, offer the flexibility of easy relocation, enabling production close to the customer or supplier. In a mathematical optimization model, the economic benefit of small-scale plants in the specialty chemicals market of polymer production is analyzed. Different scenarios created from the real data of a chemical company show that the use of small-scale plants may lead to a significant reduction in total costs that is mainly due to the transportation costs of raw materials and products.

Keywords: Location flexibility, Modularization, Small-scale production, Specialized polymers

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1 Introduction

In the chemical industry, rising requests for product diversification and shortened product life cycles lead to increased uncertainty of customer demands with regard to quantity, location, and type. To cope with the increased demand variability, flexible production plants are required especially in the field of specialty chemicals. As demonstrated by various examples, small-scale modular production plants can offer this much-needed flexibility [1]. The concept even enables the installation of small-scale production systems in standard transportation containers. This allows small-scale production systems to be easily relocated by truck enabling spatial adaptability of production capacities to customer demands. Owing to the small size, new production processes can be designed at a production scale in the laboratory, and time-to-market is further reduced by using standardized apparatuses [2].

This short communication presents a case study to investigate the economic benefits of small-scale production systems for the production of specialized polymers. The paper is based on the previous results from Becker et al. [3], with a stronger focus on chemical engineering. Real data provided by a large German chemical company is used to create a realistic scenario. A mathematical optimization model [3] is applied to prescribe an efficient production network structure with small-scale plants. Eight scenarios with different technological options and supply chain structures with respect to the production network costs are assessed.

Small-scale production can offer numerous advantages in markets which require high flexibility compared to world-scale production plants [4–8].

2 Flexibility of Small-Scale Modular Production Systems

Small-scale modular production systems combine the advantages of standardization, modularization, and transformability. The idea behind modular plants is to combine multiple independently functioning production units to create a chemical process. This idea leads away from plants dedicated to producing one product towards a production network of multiple smaller plants which offers an enhanced process and product flexibility [9].

Small-scale modular production systems are especially suitable for areas of the chemical industry in which highly changing demand occurs. The installation of small-scale plants in
standard containers allows for easy relocations of the production system, e.g., by truck. Thus, spatial adaptability of production capacities is enabled [10,11]. If the demand changes regionally, small-scale plants are able to satisfy these changes quickly.

Furthermore, the concept of small-scale production systems allows for rapid process development and scale-up in the laboratory using standardized, production-scale apparatuses. The time-to-market is significantly shortened in comparison to a typical production plant [7]. By combining standardized apparatuses of different types within one production system or by using multiple production systems, a production facility gains the ability to manufacture different products. As a result, small-scale production systems possess high flexibility to react to changes in both geographic demand shifts and changing product needs.

3 Modular Production Systems for the Production of Specialized Polymers

Within this study, a multiproduct process representing the above-mentioned characteristics is adopted [12]. The proposed multiproduct batch process is the last step in the production of specialized polymers. Commonly, these polymers are produced in multiproduct plants in which a base polymer is mixed with different additives in agitated vessels under temperature control. The different additives are mixed with the base polymer to change their characteristics in terms of, e.g., UV protection, plasticizers, and color. A major disadvantage of the common type of batch-wise production are dead times due to the cycle of filling, mixing, emptying, and cleaning the vessel in which the reaction takes place. Furthermore, the size of the agitated vessel limits the minimum production quantity, since it is not economically viable to produce very small quantities.

To overcome limitations in batch operation to produce polymers of different characteristics, a small-scale continuously operated process using different apparatuses is proposed. Fig. 1 displays the flow chart of the continuously operated small-scale plant for the production of the specialized polymer. The complete process consists of three independent containers, each fulfilling a certain assignment.

In this case, the base polymer is pumped from the tanks to the production container by eccentric screw pumps. In the production container, the base polymer is heated to 25°C in a heat exchanger and conveyed into a static mixer of type MX. To ensure sufficient mixing quality, it is necessary to ensure laminar flow within the mixer which can be reached by ensuring suitable residence times. The additives are stored in a separate additives container which is equipped with pumps. Depending on the desired product, the needed additive is pumped from the additive container to the production container and mixed with the base polymer.

The production container can be equipped with multiple static mixers to produce various polymers with different specifications concurrently. If needed, pipes, static mixers, and heat exchangers are cleaned with a solvent. The solvent is pumped to the production container to remove residues of previously

Figure 1. Flow chart of the proposed process in small-scale production systems adopted from [3].
used substances in the equipment. Within the cleaning container, the solvent is regenerated by a membrane module to minimize solvent loss. Utilities that are required for the process are electricity and heated steam and have to be provided externally. The final polymer consists of 98% base polymer and 2% additives.

4 Case Study

4.1 Scenario Description

For the evaluation of the economic benefits of small-scale production systems, different scenarios are investigated using real customer data. As potential locations, where small-scale plants can be operated, 100 corporate and industrial sites throughout Europe are considered. The requirements for the operation of small-scale plants are mainly sufficient space and the availability of the required utilities.

Fig. 2 illustrates all potential production facilities, suppliers, and customers. To operate a production facility, a certain number of staff is required. Furthermore, it is assumed that due to the moderate level of technical complexity of the plant it can be quickly assembled and dismounted, loaded onto a truck, and transported to a different location.

Using the presented production process, eight different scenarios are proposed. Hereby, the base scenario is the production of specialized polymers with small-scale plants while receiving the base polymer from a central supplier. To account for location flexibility, small-scale plants can be placed close to the customer as well as close to a supplier. Therefore, decentralized suppliers are assumed from which the base polymer can be received.

The plants are producing one product (mono production), decentralized in close proximity to the customer, with central sourcing (C) and local sourcing (L). By changing the equipped static mixer to three different types, one plant is able to produce polymers with different specifications under the prerequisite of different additives enabling product flexibility (P). Nevertheless, it is assumed that the size of each static mixer is then downsized due to the limited space in the production container. Since the staffed costs (S) in chemical plants are responsible for a significant ratio of the overall fixed costs, the advantages of autonomous production (A), in which less personal effort is needed, is considered. By combining the different options, the various scenarios are achieved, as presented in Tab. 1.

Using a mathematical optimization model, the production network costs for fulfillment of all customer demand over the course of one year are minimized. The mathematical model represents a mixed-integer linear programming model, and it is solved to optimality using commercial solvers. The optimization model determines the best production facility locations, the number and type of production modules at each facility, as well as all material and product flows from supplier to customer. For a more detailed discussion of the mathematical model, the interested reader is referred to [3, 8, 12].

Table 1. Survey of the scenarios.

| Scenario | MSC | PSC | MAC | PAC | MSL | PSL | MAL | PAL |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| Local sourcing options | – | – | – | x | x | x | x | x |
| Autonomous production | – | – | x | x | – | – | x | x |
| Product flexibility | – | x | – | x | – | x | – | x |

Figure 2. Survey of the locations of customers, potential production locations, and local suppliers adopted from [3].
4.2 Results

The resulting costs for the fulfillment of all customer demands over the course of one year are given for each scenario in Fig. 3. Facility and module operation costs, as well as relocation costs, are infrastructural costs of the production network. Sourcing, production, and delivery costs are accounted for per unit and are directly connected to customer demands. It is apparent from the resulting costs in Fig. 3 that considering either local sourcing, autonomous production facilities, or product flexibility leads to a reduction of total costs. Taking local sourcing as an option for sourcing base polymer leads to a significant reduction of total costs in all cases. The advantage of local sourcing is mostly independent of the other aspects of this analysis. This is in particular due to the large impact of raw material transportation costs on the total costs.

Exemplary results for the optimal structure of the production network in case of scenarios MSC and PAL are demonstrated in Figs. 4 and 5. The grey lines represent the transportation distances between each location. What stands out in these figures is that the introduction of local sourcing, autonomous production facilities, and product flexibility leads to considerably shorter transportation arcs. A high number of production facilities are positioned in close proximity to both suppliers and customers. Even though the total number of production facilities operated increases, transportation costs are reduced by up to 30%. Total costs are diminished by 35%.

While product flexibility leads to a reduced production capacity due to smaller apparatus size, a single plant is still mostly sufficient to serve customer demands in the vicinity of a production facility. In contrast to scenario MSC, customers are thus typically served from the closest production facility in scenario PAL owing to product flexibility. As a result, the average length of transportation arcs is significantly reduced.
The implementation of autonomous facilities results in lower personnel costs (Fig. 3). While costs for each module increase, the fixed costs for facility operation are greatly reduced. Regardless of the availability of local sourcing options, the cost reduction of introducing autonomous production facilities is higher than the cost reduction of product flexibility. If autonomous production facilities with product flexibility are available, the combined cost reduction will be higher than the sum of the individual cost reductions. This indicates that there are potential synergies in combining both options.

Furthermore, autonomous production systems bear a high potential of reducing costs and accountability for staff in the scope of Industry 4.0. They can lead, e.g., to shorter downtimes by making assembly of modular production systems quicker and easier. However, the technical challenges of implementing standardized production system connections to its environment, including all system information streams are high. Further evaluations have to be carried out to prove feasibility and support the implementation.

For the application considered throughout this paper, the mixing quality is the main limiting factor for the capacity of the static mixers. Since these limits are rarely exhausted, a modular system with several static mixers, which results in product flexibility, should be preferred. As a result, a polymer production plant, in which multiple products can be produced, exhibits similar cost reduction while maintaining lower technical barriers in comparison to autonomous production. If local sourcing options are available, decentralized production with small-scale plants can improve the production network efficiency. In addition, flexibility with respect to the product range leads to improved production network efficiency.

5 Conclusion and Outlook

The benefits of modular small-scale plants for the production of specialized polymers were demonstrated. Eight scenarios were created from real data and used to analyze key aspects with respect to the implementation of small-scale plants and the structure of the production network for this specific case. Small-scale production systems that offer enhanced flexibility can increase the responsiveness and efficiency of the production network. One main advantage for the responsiveness is the ability to locate production facilities in closer proximity to customers. The availability of local sourcing options allows for an even greater benefit, as production facilities may ideally be located close to local suppliers and customers at the same time. The efficiency of the production network can be even further increased if the product range of the small-scale plants is flexible and if the production facilities operate autonomously. However, the implementation of product flexibility is highly dependent on technological feasibility. In this case, due to the moderate complexity of the apparatuses integrated into the production plant, it is assumed to be a realistic option.

Autonomous production facilities are also highly interesting since they simplify the operation of the plants. Nevertheless, further investigations have to be performed to evaluate the technological boundaries and required expenditures.

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Abbreviations

A autonomous production
C central sourcing
L local sourcing
M mono production
P product flexibility

References

[1] Final Report Summary – P³ Factory (Flexible, Fast and Future Production Processes), Bayer Technology Services GmbH, Leverkusen 2013. https://cordis.europa.eu/project/rcn/92587/reporting/en
[2] S. Lier, S. Paul, D. Ferdinand, M. Grünewald, Chem. Ing. Tech. 2016, 88 (10), 1444–1454. DOI: https://doi.org/10.1002/cite.201600015
[3] T. Becker, B. Bruns, S. Lier, B. Werners, J. Bus. Econ., in press. DOI: https://doi.org/10.1007/s11573-020-01019-4
[4] A. Brodhagen, M. Grünewald, M. Kleiner, S. Lier, Chem. Ing. Tech. 2012, 84 (5), 624–632. DOI: https://doi.org/10.1002/cite.201100220
[5] S. Lier, M. Grünewald, Chem. Eng. Technol. 2011, 34 (5), 809–816. DOI: https://doi.org/10.1002/ceat.201000380
[6] S. Sievers, T. Seifert, M. Franzen, G. Schembecker, C. Bramsiepe, Chem. Eng. Sci. 2017, 158, 395–410. DOI: https://doi.org/10.1016/j.ces.2016.09.029
[7] H. Mothes, Chem. Ing. Tech. 2015, 87 (9), 1159–1172. DOI: https://doi.org/10.1002/cite.201400133
[8] T. Becker, S. Lier, B. Werners, Eur. J. Oper. Res. 2019, 276 (3), 957–970. DOI: https://doi.org/10.1016/j.ejor.2019.01.066
[9] T. Seifert, S. Sievers, C. Bramsiepe, G. Schembecker, Chem. Eng. Process. 2012, 52, 140–150. DOI: https://doi.org/10.1016/j.cep.2011.10.007
[10] T. Bieringer, S. Buchholz, N. Kockmann, Chem. Eng. Technol. 2013, 36 (6), 900–910. DOI: https://doi.org/10.1002/ceat.201200631
[11] K. van Kranenburg, C. Sofra, D. Verdoes, M. de Graaff, Small-scale Flexible Plants: Towards a more Agile and Competitive EU Chemical Industry, TNO, Delft 2015. https://repository.tno.nl/islandora/object/uuid:639798ee-c8ca-4949-9acf-24aca45ee2f5
[12] T. Becker, B. Bruns, S. Lier, B. Werners, in Operations Research Proceedings 2018 (Eds: B. Fortz, M. Labbé), Springer, Cham, Switzerland 2019.