Part IV
Economics and Eco-efficiency Analyses

13
The Economic Potential of Microreaction Technology

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13.1
Introduction

The fine chemical and pharmaceutical industry (FCPI) has been characterized for decades by batch processes in both laboratories and production plants. The rationale for this can be explained by the short life cycles and relatively small outputs in this area. Because of the comparatively high flexibility (capacity, assortment and structure flexibility) of batchwise working plants, continuously operating plants did not appear economically applicable in the past.

The commercial interest in microprocess engineering has clearly been increasing, not least in the FCPI. This increase is based on novel ways of process intensification offered by this engineering approach (e.g. [1]), combined with further reactor and process engineering advantages such as process safety, legislation and modularity [2]. Although process intensification has been demonstrated [3], the question remains whether microreaction technology (MRT) can lead to economic benefits. This topic was intensely discussed between experts for the first time during the AIChE Spring Meeting held in Orlando, FL, USA, in 2006. The following aspects were highlighted as key aspects in the commercial breakthrough of microprocess engineering: process intensification (especially in terms of selectivity), standardization, availability of skilled employees and serious cost analyses to quantify the economic potential.

The results of the first worldwide studies dealing with potential and cost analysis associated with the use of microreaction technology in the FCPI are discussed below. Their perspectives cover the industrial point of view and also that of a supplier of MRT. Moreover, academic and standardized evaluation methods are presented.

First, the results of a four-stage potential analysis developed by Merck (Darmstadt, Germany), together with the Technical University of Clausthal are discussed. This analysis starts with a technological evaluation of MRT to achieve finally a business view [4]. Next, a short summary of a study from the fine chemical and pharmaceutical company Lonza (Visp, Switzerland) dealing with capital (CAPEX) and operational (OPEX) costs for several pilot microchemical processes is presented [5]. The picture is rounded off by cost analyses of the chemical producer AzurChem, prepared in

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cooperation with IMM [6], and of the aqueous Kolbe–Schmitt synthesis of 2, 4-dihydroxybenzoic acid [7].

13.2
Potential Evaluation of Microreaction Technology at the Stage of Process Development

13.2.1
Introduction to Potential Evaluation Methodology

In order to rate the efficiency of new technologies in the process industry, methods involving the evaluation of alternative energies and the impact of products and processes on the environment can be considered [8–10]. These methods for the evaluation of potential cannot be generalized because they are too case specific and the material aspect is not sufficiently considered. Therefore, no generally accepted rules are available.

Schmalz *et al.* [4] suggested defining the potential of MRT as its efficiency concerning the possible reductions in costs during process development and production compared with batchwise operations. Here, potential is differentiated between theoretical, technical, material and economical potential (Figure 13.1).

The theoretical potential describes the maximum attainable savings with the use of MRT. The technical potential describes the possible savings considering existing unit

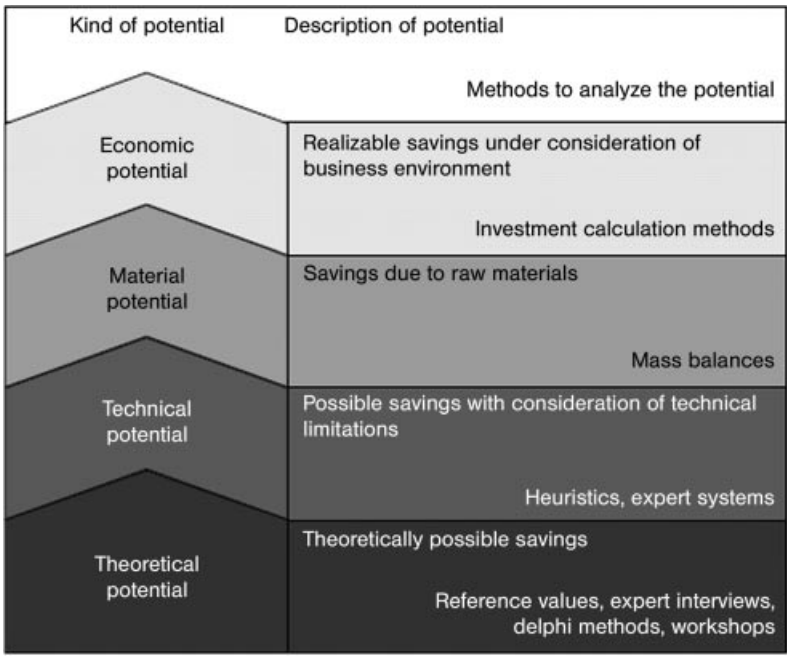


Figure 13.1 Kinds of potential, their descriptions and methods of analysis [10].

operations. The material potential is quantified as the savings of raw materials in relation to batch technology. Finally, the economic potential sets the savings calculated on the basis of the material potential in relation to economic key indicators.

The maximum attainable savings depend on the unit operations which are technically feasible and meaningfully applicable. Beyond that, the total process has to be considered for an evaluation. Process chains in the FCPI possess in particular a high proportion of downstream operations, which have to be included in any evaluation. Further, this branch is identified with very high product prices of up to several hundred thousand euros per kilogram and a large number of chemical stages. The production amounts in the FCPI lie in the range from several hundred kilograms up to several tons per year.

13.2.2 Reaction

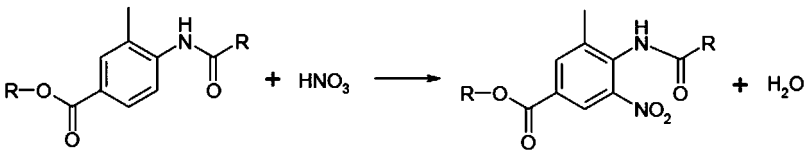
Nitration reactions are very important in the synthesis of fine chemicals. Because of the highly exothermic reactions, they are suited to the use of microreaction systems. The potential analysis by Schmalz *et al.* [4] is based on the synthesis example shown in Scheme 13.1.

The reaction has an exothermic heat of $-191\ \mathrm{kJ\ mol^{-1}}$, which causes an adiabatic temperature rise of 111 K. During the reaction, the 6-nitro isomer will be formed in addition to the 5-nitro isomer, and has to be separated in a complex downstream process. The results of the nitration in the microreaction and in a batch system were compared. The best alternatives are nitration with dichloromethane–acetic anhydride–nitric acid and acetic acid–acetic anhydride–nitric acid. In both cases less than 1% of the 6-nitro isomer was detected (Table 13.1). With a purity of >99% the specifications of the intermediate were attained and the downstream process could be omitted.

The results of the potential analysis are discussed below based on nitration with acetic acid–acetic anhydride–nitric acid.

13.2.3 Theoretical Potential

In this case, the possible saving by using microreaction technology is to be understood as the theoretical potential. It is assumed that there are no restrictions regarding technical, material and economic constraints. Hence the theoretical potential represents an upper limit of the reduction in costs during the process development and production compared with the conventional batchwise process development and production (Table 13.2).



Scheme 13.1 Reaction scheme for the nitration of 4-phenylmorpholin-3-one.

Table 13.1 Possible nitration alternatives evaluated by Schmalz *et al.* [4].

Nitration alternative	Residence time (min)	By-product (6-isomer) (%)
Sulfuric acid–nitric acid (batch)	40 (0 °C)	~5
Dichloromethane–acetic anhydride–nitric acid	1 (20 °C)	<1
Acetic acid–acetic anhydride–nitric acid	12 (20 °C); 4 (40 °C)	<1

The results of Schmalz *et al.* [4] indicate that the application of a microreaction system can reduce the costs for optimizing the synthesis by 74%.

13.2.4 Technical Potential

The technical potential represents the first subset of the theoretical potential. It considers restrictions in using MRT. These restrictions can be determined, for example, with expert systems and heuristics [11, 12]. The following obstacles for an MRT system [12] were considered:

- Suitable unit operations for the execution of the process cannot be provided (e.g. crystallization).
- Suitable parameters (concentration, etc.) are missing.
- Due to process intensification, decomposition reactions are not avoidable.
- There are no resistant reactor materials available.

Therefore, only reactions steps and aqueous downstream processes that are currently feasible with MRT are considered in the evaluation of Schmalz *et al.* [4]. They estimated the overall savings on the laboratory scale at 82%.

13.2.5 Material Potential

The specific material costs and costs of waste streams are considered in the material potential. The investigations by Schmalz *et al.* [4] showed a slightly improved conversion regarding the key components. Nevertheless, the costs of raw products

Table 13.2 Capital and running costs.

Capital costs	Running costs
Depreciation	Personnel costs
Building	*Maintenance costs*
Microreaction plant	Building
Imputed interest	Microreaction plant
Building	Costs of analytics
Microreaction plant	Other costs

Table 13.3 Costs of chemicals for process development compared with batch (100%).

	MRT
Cost reduction for running one synthesis (%)	49
Overall cost reduction for chemicals during process development (%)	41

form only a small part of the overall costs for process development (0.1%). Regarding this, the costs of chemicals in process development can be reduced by up to 41% by MRT (Table 13.3).

13.2.6
Economic Potential

The economic potential is the potential that can be realized under the constraints in the FCPI. For the determination of the economic potential investment, calculation methods are used.

The amortization period is defined as the assigned capital in relation to the average return flows. A minimum payback period of 3 years was determined as a benchmark. In order to reach this benchmark, at least three process developments per year have to be accomplished in one MRT system on the laboratory scale. Under these conditions, the application of MRT compared with the batch system is beneficial. When only one reaction is optimized, the resulting payback period will be 6 years.

13.3
Current Benefits and Drawbacks of Microreaction Technology in Commercial-Scale Production

As discussed earlier, productions in the FCPI are commonly managed in so-called production campaigns that rely mainly on batch or semi-batch processes [13]. Roberge *et al*. of Lonza Visp (Switzerland) [5] investigated the benefits and drawbacks of microreaction technology in the FCPI to learn more about this alternative technique. Their results are discussed in the following section.

The campaigns in the FCPI are typically operated on a train/stream approach where a solid key reagent is introduced and a crystalline product is obtained. The average characteristics of a production campaign are presented in Table 13.4. Unit operations such as reaction, distillation, liquid–liquid extraction and crystallization are fundamental procedures in a multi-purpose train. A conventional batch vessel is able to perform all these operations, allowing flexibility and versatility in the production.

Based on a recent review [14], an average of 8.1 steps (chemical transformation) are usually required for the production of a final active pharmaceutical ingredient (API) from starting materials obtained from the fine chemical industry. Under such

Table 13.4 Average characteristics of 22 different processes in the FCPI relating to large-scale production campaigns [5].

Production (t per year)	Duration (weeks)	Productivity (t per day)	Yield (%)	Unit operations	
				Reaction	Workup
44	4–8	1.5	77	2.1	2.7

conditions, the cost drivers are different depending on whether a reaction step is located close to the API or at the beginning of the supply chain. Close to the API, the main cost driver is the yield. An increase in yield not only decreases the cost of a single step, but also increases the efficiency of all previously performed steps. Thus, the typical gain for one step is multiplied by a factor that is a function of the number of synthetic steps that occurred ahead of that step.

On the other hand, for intermediates at the beginning of the supply chain, the dominant cost driver is the labor cost. This feature is demonstrated in Figure 13.2, which presents the typical distribution of operating expenditures (OPEX) in a fine chemical plant. The importance of labor cost is even amplified if quality insurance (QA/QC) is taken into account and changeover and cleaning expenditures contribute to further labor costs. In addition, if one assumes that most of the small drug molecules (MW < 550) are derived from the petroleum industry (natural product <5%), then the cost of raw material becomes insignificant and the overall costs are attributed to manufacturing [14]. Consequently, it is not surprising to observe a shift

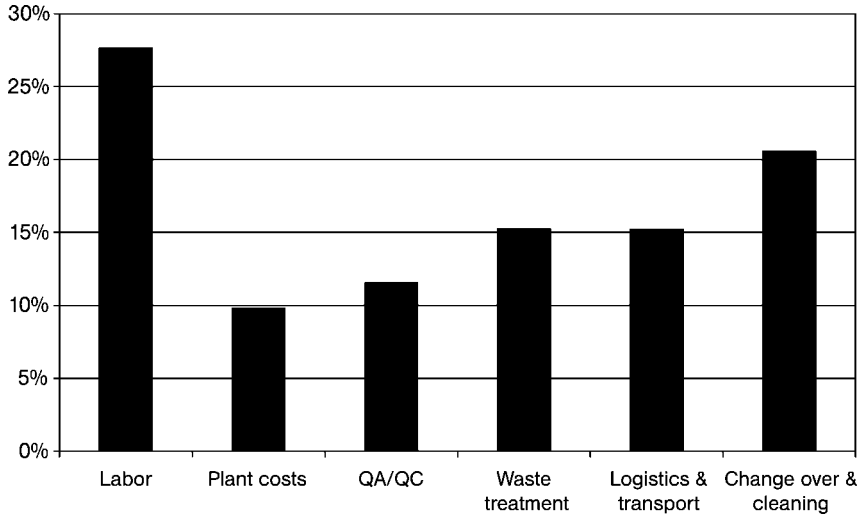


Figure 13.2 Typical distribution of operating expenditures (OPEX) in a fine chemical plant based on a campaign analysis [5].

of the fine chemical industry towards countries with significantly lower labor costs such as China and India.

Thus, microreactor technology, by allowing continuous processes, touches at the heart of fine chemical manufacturing processes, namely it reduces the amount of labor required to run a process. It reduces the amount of labor because it reduces the number of unit operations (or procedures) accomplished by workers. Those operations are performed *in situ* through an automated system and an appropriate microreactor setup (toolbox concept). The relation between continuous operations and labor is well established in other industries such as the petroleum industry, leading to highly automated and efficient processes.

Thus, Roberge *et al.* [5] concluded that the development of an appropriate toolbox is a prerequisite to allow high flexibility and versatility in a production environment. The toolbox concept must be viewed as a modular approach where a production unit is adapted to a chemical system. On doing so, one must take into account the physical–chemical characteristics of a reaction, such as

- the reaction kinetics leading to various residence times
- the reactions phases: solid–liquid–gas.

Workers at Lonza have depicted the kind of reaction that prevails in the FCPI [5]. As illustrated in Figure 13.3, the reactions were classified in three main classes: Type A, B and C. The classes suggest, of course, the type of modules required to handle these reactions.

Type A reactions were defined as very fast ($t_{1/2} < 1$ s) and mainly controlled by the mixing process. The heat and mixing demand in a small localized zone is so high that

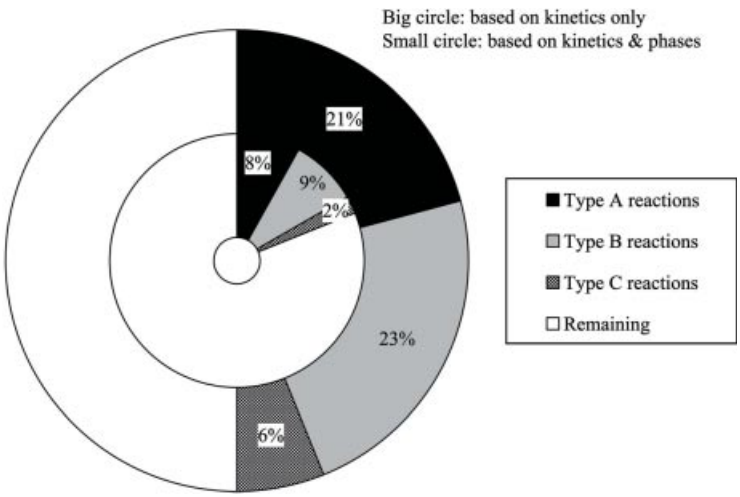


Figure 13.3 Analysis of 86 different reactions carried out at Lonza in three main classes (Types A, B and C; see text) based on reaction kinetics (large circle) and reaction phases (small circle) [5].

even a standard microreactor has difficulties in coping with the thermal management so that a hot spot is generated. The answer for this type of reaction is a multi-injection microreactor [15]. Type B reactions were defined as rapid but nevertheless having a reaction time of a few minutes. These reactions require a microstructure at the reaction start but can be completed under controlled conditions with conventional apparatus such as cooled/heated coils. Type C reactions were defined as slow batch processes that pose, however, a thermal hazard problem. This kind of reaction can be performed in conventional equipment such as static mixers and shell and tube heat exchangers or more progressively in a BHR Flex reactor (www.bhrgroup.co.uk) or Sulzer SMR reactor (www.sulzerchemtech.com). For this kind of reaction, a microstructure is needed when heat is suddenly generated, such as in autocatalytic reactions [16].

The outcome of the reaction analysis is that up to 50% of the studied reactions would have sufficient rapid kinetics to be operated in a microreactor (Figure 13.3). One of the main hurdles, however, remains the handling of solids that reduces the number of reaction candidates to less than 20% [5]. Hence the development of multipurpose microreactor modules that can deal with solid phases is highly attractive. This is also true for liquid–liquid and gas–liquid reactions where the solubility of one phase in the other brings an additional complexity to the development of the modules.

Roberge *et al.* [5] also demonstrated that the scale-up coefficient to increase the batch reaction volume is as low as 0.3 (investment costs $\sim R_{\text{volume}}^{0.3}$), meaning that a batch vessel is fairly cost effective in increasing the volume. This scale-up criterion is only valid for slow reactions, i.e. reactions that are controlled by the kinetics. For the other reactions (Type A and B) that are controlled by mixing and heat exchange, the heat exchange surface area is a more appropriate scale-up criterion. Hence the miniaturization effect of the microreactor leading to a large surface area per unit reaction volume can reduce capital expenditure under some circumstances. Therefore, in the economic analysis of a process, it is important to determine the threshold value of reaction time/residence time where a continuous process is no longer economically attractive.

A small number of Type C reactions cause real scale-up problems (around 6% only as indicated in Figure 13.3). Therefore, it is not surprising to observe that the reaction mixture is generally diluted for the majority of slow reactions. It seems that from the very beginning, the process development chemist approaches the scale-up problem by diluting the reaction mixture. The use of solvent is a pragmatic approach to avoid future scale-up problems; however, it renders the process inefficient with a high consumption of raw materials.

Hence there is considerable potential for these slow reactions to be intensified. Microreactor technology/continuous processes can here also play a critical role in process development. It allows reactions to be conducted almost solvent free [16] and it permits the boiling point of a mixture to be easily extended by applying pressure [17]. In addition, the combination with other technologies such as microwave techniques is an avenue for further synergies [18].

13.4
Cause variables of Profitable Production of Microstructures

13.4.1
Introduction

The profitability of a production process is influenced by a huge number of variables, but commonly only a few of them have a major impact. In the following, this will be exemplarily demonstrated on the formation of 4-cyanophenylboronic acid, investigated by Krtschil *et al*. [6]. An economic fine chemical process of the customized chemical producer AzurChem serves as the basis of the calculations. This process uses the benefits of microprocess technology supplied by IMM and is representative of several other fine and specialty chemical manufacturing processes proprietary to AzurChem. The conclusions from the particular case are extended via some potential case scenarios of conceivable improvements by means of capacity or selectivity increases. The chosen scenarios are based on the fact that microstructured reactors may improve selectivity [2] and in this way reduce the costs of chemical starting materials, waste disposal and energy. This can sometimes be achieved by simply transferring a batch protocol into a continuous-flow microreactor operation with increased mass and heat transfer and kinetically derived (shorter) residence times. The latter may also impact the operator costs. In many other cases, however, the simple repetition of batch processing protocols is not enough, and process intensification demands new tailored protocols for chemical microprocess engineering, termed "novel process windows" [19]. Both cases are considered by the authors [7]. In this way, some decisive variables for the suitability of this novel technology are revealed, such as how process intensification translates into business drivers.

13.4.2
Cost Calculation Methodology

Significant revenue shares for fine chemical plants relate to raw material supply, waste disposal, operator salaries and the investment in the plant itself. Accordingly, the cost analysis includes both fixed and variable costs, roughly corresponding to the CAPEX and OPEX costs, respectively. The variable costs include costs of reagents, the operator's salary, energy consumption and disposal. The fixed costs are subdivided into product-related fixed costs and remaining fixed costs. The main part of the product-related fixed costs includes the equipment costs, which encompass both the existing microreaction plant including three microstructured reactors, four pumps, valves and piping, measurement and control technology, cryostat and installation costs and the necessary devices for the purification. The last cost variables cover costs which arise for a company independent of the relation to a specific product. The remaining fixed costs include administration costs and costs of offices and of sales activities, for instance. In accordance with AzurChem's practice, an amortization period of 5 years was assumed.

13.4.3
Chemical Reaction Investigated

Boronic acids are used as intermediates for the synthesis of pharmaceuticals and fine chemicals, such as for Suzuki couplings. As representative of this class of chemical intermediates, the manufacturing process of the high-value 4-cyanophenylboronic acid was chosen for investigation. A key feature of the reaction is the high price of the raw materials and of the product 4-cyanophenylboronic acid; therefore, the process is characterized in the following as dominated by the high-value raw materials.

The synthesis of the product is operated as a continuous process in the microreaction plant [20]. The subsequent purification steps such as distillation are performed batchwise.

13.4.4
Cost Analysis of the Existing Microchemical Process

For the analysis of the decisive variables of a profitable microchemical process, different case scenarios were studied based on the existing manufacturing process. The calculations were based on an average yield of the process which could be achieved of 75%, including not only the reaction yield but also the loss of the product within the purification process.

Figure 13.4 emphasizes the large share of variable costs, amounting to 63% compared with the product-related fixed costs which amount only 4%. This is caused by the use of high-value fine chemical raw materials and by the large share of operator costs for any chemical process (at least when based on German salary standards, as done here). The investment costs for microprocess equipment therefore cannot be a major decision driver in this case, whereas the importance of suitable microprocess engineering (also for future process optimization) is evident, directly affecting the

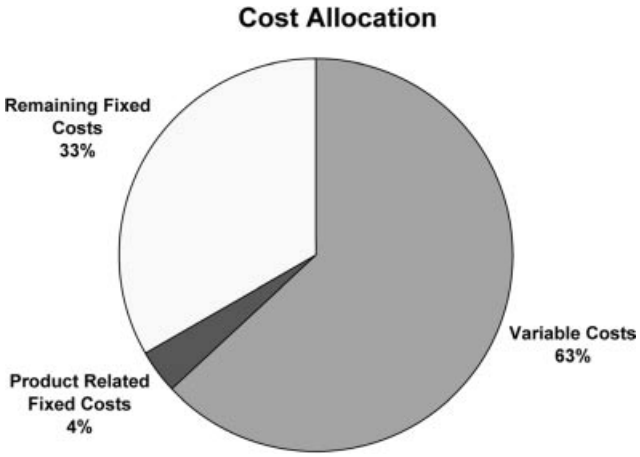


Figure 13.4 Cost allocation of the existing process.

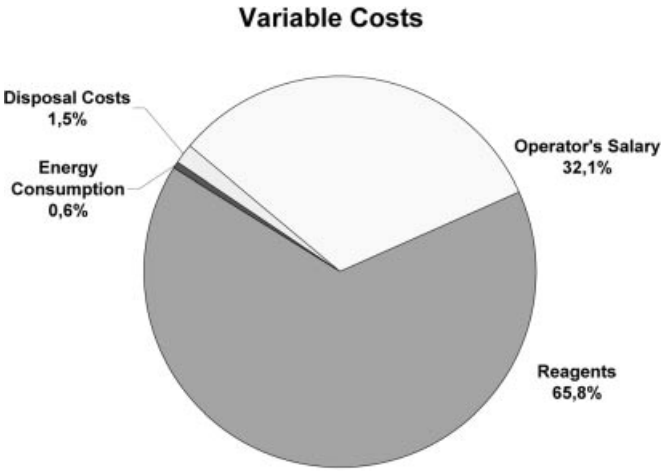


Figure 13.5 Breakdown of the variable costs.

variable costs. This is in accordance with other fine chemical studies carried out by some of the investigators [7]. These studies also demonstrate that the costs of the microstructured reactors usually amount to less than 10% of the overall plant-related costs, which go along with the costs of conventional plant engineering. Therefore, the microstructured reactor costs have almost no relevance for the overall decision for or against this new technology, but rather their performance and reliability are main drivers. The fraction of the remaining fixed costs here comprises one-third of the total costs.

In the case of the variable costs, there are only two major constituents, which represent together almost 98% (Figure 13.5). The costs of the starting substances comprise 66% and the operator salary is 32%. This high proportion of the raw material costs indicates that it can be economically beneficial to produce high-value chemicals with microprocess technology even in countries with a high salary level.

13.4.5
Influence of Possible Improvements on the Manufacturing Costs

In addition to the evaluation of the real existing micro chemical process, a number of case scenarios were also described by Krtschil *et al.* [6]. As an example, the capacity increase was considered. This can be done equally well by enlargement of the internal dimensions in a certain range without losing performance, called "smart dimensioning" [17], as by the so-called "external numbering-up", which means multiplication of the microdevices themselves. In the former case, two variants, assuming 5- and 10-fold increases in capacity, were considered, and in the latter case 10 microdevices working in parallel.

Setting the total costs of the real microchemical process at 100%, a dramatic decline in costs can be achieved for the three different scenarios with increased capacity (Figure 13.6). The total costs are reduced to one-third (33%) for the microchemical

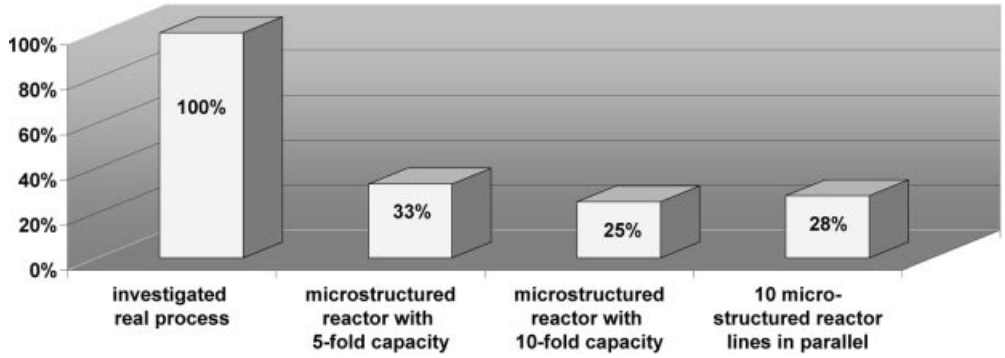


Figure 13.6 Comparison of total cost for different case scenarios.

process with 5-fold capacity and a further decline to 25% in the case of 10-fold higher capacity. The authors concluded that both process intensification and numbering-up provide a practicable way to increase profitability further.

13.4.6
Cost Analysis of the Aqueous Kolbe–Schmitt Synthesis of 2,4-Dihydroxybenzoic Acid

Another study [7] was reported based on process intensification via "novel process windows" [19], which permitted a reduction in the reaction time required of up to three orders of magnitude. For this reason, synthesis in a microreactor becomes competitive compared with the batch process. Otherwise, when using the conventional operating conditions, synthesis in a microreactor would generate formidably higher costs.

The base case of the aqueous Kolbe–Schmitt synthesis of 2,4-dihydroxybenzoic acid is calculated with a five-tube reactor allowing a theoretical production rate of 4.4 t p.a. (assuming 8000 h p.a.). The product-related fixed cost of about €1 per kilogram of product, derived from the investment cost by dividing by the amortization time of 7 years, are very small compared with the operational costs of €91 kg^{-1}. The main and approximately equal portions of the operational costs are the raw material cost and operator salary when a quarter of the hourly wage rate of manpower is assumed (Figure 13.7).

Further process intensification which results in a 10-fold higher throughput leads to a dramatic decrease in operating costs (Figure 13.8) and also a decrease in fixed costs. The main driver is the decline in the operator's salary. A similar result could be obtained by external numbering-up, that is, with 10 reactors in parallel.

In both cases, for the production of 4-cyanophenylboronic acid and also for the synthesis of 2,4-dihydroxybenzoic acid, order-of-magnitude changes in productivity can be obtained by MRT, which may also decrease the plant size per given production rate, targeting the operator salaries and the plant investment. This is achieved not only by exploiting the engineering potential of microstructured reactors, but also by using the latter to utilize essentially "novel organic chemistry", such as operation at

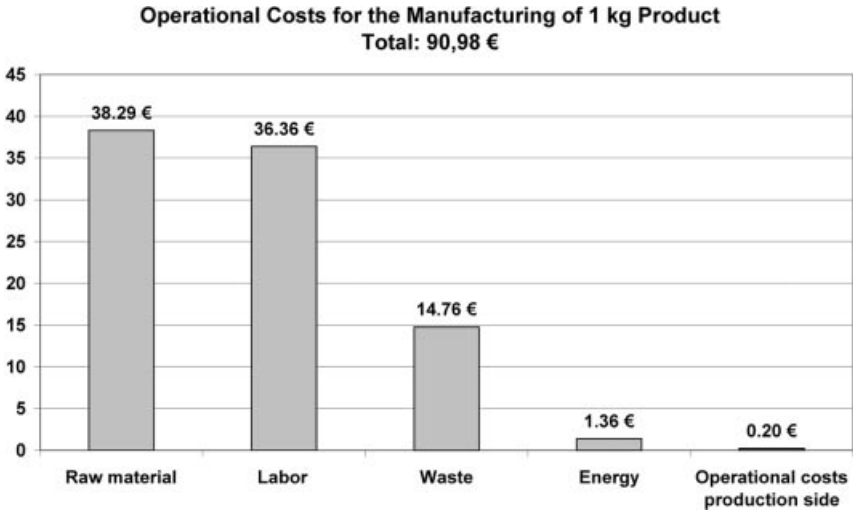


Figure 13.7 Variable costs, realized process.

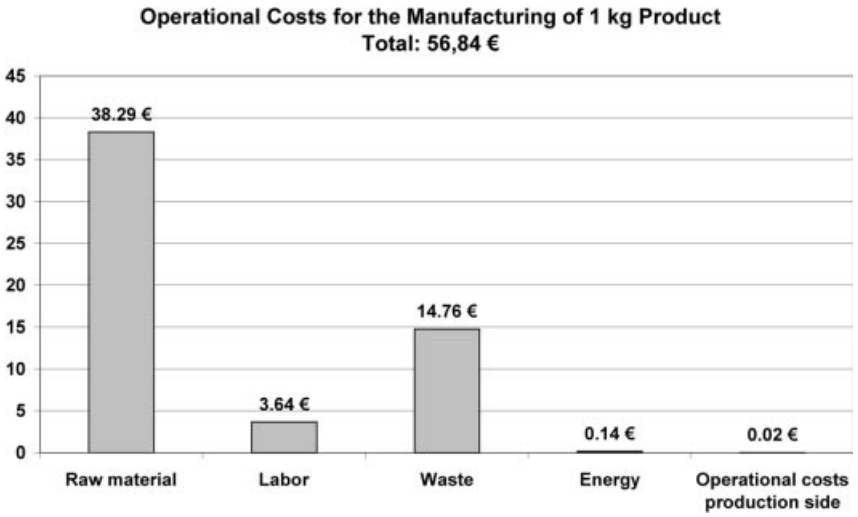


Figure 13.8 Variable costs, process intensification.

high temperatures combined with high pressures, resulting in substantially shortened residence times [17].

13.5 Conclusion

An overview of different approaches to evaluate the economic potential of MRT, particularly with regard to the FCPI, has been given.

First, the results of the potential analysis developed by Merck (Darmstadt, Germany) together with the Technical University of Clausthal indicate that microreaction technology can be profitably used during the stage of process development [4]. For the evaluation of microreaction technology, a method using four different types of potential (theoretical, technical, material, economic) were provided and systematically applied to process development in the FCPI. The theoretical potential represents the upper limit of possible savings with an MRT system. It was shown that the theoretical potential of the considered portfolio amounts to 74% of the total costs. For the investigation of the technical potential, technical restrictions were considered. From the results of this stage of evaluation, it could be shown that certain reaction steps can be enhanced by an MRT system. The technically realizable potential has been ascertained to be about 59% of the total costs, and the material potential was nearly identical with the technical potential. The last stage, the evaluation of the economic potential, was determined by a minimum payback period of 3 years as a benchmark of the evaluation. In order to reach this benchmark, at least three process developments per year have to be realized under the given conditions on the laboratory scale. Then the MRT system becomes beneficial compared with the batch system.

Second, a study performed by Lonza (Visp, Switzerland), dealing with current benefits and drawbacks of microreaction technology, was presented [5]. The authors depicted the kind of reaction that prevails in the FCPI and classified them in three main classes, Type A, B and C (very fast, rapid and slow reactions, respectively). They reasoned that up to 50% of the reactions performed at Lonza could benefit from continuous processing. For 44% of them a microreactor would be the preferred reaction device. However, the handling of solids reduces the number of reaction candidates to less than 20%. The authors therefore emphasized the development of multi-purpose microreactor modules that can deal with solid phases. Further, Roberge *et al.* [5] emphasized the potential of MRT to reduce labor costs by highly automated and efficient processes.

Finally, cost analyses of the chemical producer AzurChem, prepared in cooperation with IMM, and of the aqueous Kolbe–Schmitt synthesis of 2,4-dihydroxybenzoic acid were discussed [6, 7]. In the former study, a commercially applied manufacturing process for the fine chemical 4-cyanophenylboronic acid was evaluated. The results indicated that optimization of operational (variable) costs can be the key driver to develop a business perspective for microprocess engineering. Here, two major trends were visible. The first relies on the synthesis of high-value products from expensive raw materials. Then, even the high operator costs, which otherwise dominate, are outpaced. The second strategy is based on reducing the operator costs by process intensification through microprocess engineering. In both cases, the equipment costs (microstructured reactors and balance-of-plant equipment) have a low share. Hence it was concluded that these costs should have a minor impact on the decision to adopt the novel technology, and rather the latter has to demonstrate the expected process optimization and reliability [6]. The cost analysis of the Kolbe–Schmitt synthesis highlighted the significance of the use of "novel process windows" for the commercial success of microprocess engineering [7].

13.6 Outlook

The level of today's information is very limited. Here, just a very few cases could be discussed. Any conclusion may be process specific and preliminary in conclusions, to be overtaken by new developments or different ways to approach a process problem. Hence care has to be taken with generalization. Further, a benchmarking to batch processing is needed in more detail. In general, future cost analyses have to bear a higher degree of detail, as only in this way can a parametric understanding of how to fine tune microreactor processes for optimal cost efficiency be achieved.

Another shortcoming of today's investigations is that they only consider fine chemical or pharmaceutical processes with capacities smaller than 100 t p.a. Just recently, the movement of DSM at Linz into bulk chemical microreactor processing with a capacity of more than 1000 t p.a. has increased the scope of consideration by an order of magnitude. Large-scale production has different cost shares to the examples reported here. In addition, the large-sized, high construction material-loaded microstructured reactors for such a purpose touch upon the current limits in fabrication, that is, their capital costs are high, but uncertain in the sense that reductions in costs by improved future technology are likely. In this case, reactor costs will have a major share in all costs and this will be one key to cost-efficient bulk chemical microreactor processing. Further, installation costs can even exceed the immense reactor costs by a factor of 3–5. This concerns, for example, equipment installation, electrical equipment and electrical connection or control materials and control installation.

Cost analyses also need to be extended from a reactor engineering level to process engineering issues. This includes provision of modularity, easier scalability (quantifying time-to-market), reduced plant footprint, easier legislation/fast authority approval and high shares of operation compared with plant shut-down. Full process simulations, such as done currently with ASPEN for conventional processes, are needed as a base for economical investigations.

Finally, current cost analysis studies need to be extended to new applications such as energy (fuel processing for fuel cells), home care, food and others. Here, cost structures are different and so are the customer expectations for this new technology.

Despite these shortcomings of today and challenges for future studies, it has to be stated that the few known (and the many more industry-internal, undisclosed) cost analyses have provided much encouragement to render microprocess technology a mature technology with true process intensification potential. Microprocess technology is driven by applied researchers, who have put this at the forefront at the expense of more fundamental studies. As a consequence, the technique is often expensive, but at least in some cases competitive. It is likely that cost analyses will show us the way forward for process optimization, that is, how to apply microprocess technology properly. The finding and exploitation of novel process windows will play a key role for this purpose. Here, it will be beneficial that laboratory results can already give an outline of the costing of the subsequent production process, as scale-out is fast and predictable; at least there is a potential.

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