Choose your target and … intensify!

Jeremy Double presents a practical guide to process intensification and how it can lead to commercial gains

Process intensification (PI) is an approach that can have significant benefits for some processes. However, it is only appropriate to use a technology – including PI – commercially where it offers a tangible business benefit.

Process design aims to generate the 'best' process; that is to say the process that increases the company's long-term profitability by the greatest amount. Apart from direct process profitability, however, other factors such as capital availability, time to market, process reliability and safety, health and environment (SHE) must be considered because of their potential impact on overall profit.

It is also widely recognised that to achieve the 'best' process, it is important to optimise the process as a whole and not just individual operations within the process.

There are three general approaches to PI, all of which have the aim of improving process performance:

- simplifying processes by integrating multiple process tasks in a single item of equipment;
- reducing equipment size by reducing its scale of structure; and
- reducing equipment size using an intensified field (eg, centrifugal, electrical, microwave).

Although PI is often said to have started at ICI in the 1970s, all three approaches were used long before this as part of good process development and design.

applying novel PI technologies

For a technology to be used successfully, the expected business advantages must significantly outweigh any perceived business and/or technological risks. As untried technologies have high perceived risks, it is understandable that they are not always embraced enthusiastically by industry.

One route to innovation is, therefore, to identify those processes where novel technology is essential for the process to succeed. However, chemists involved in the early stages of process development are more likely to work with chemistries they are confident can be scaled up using conventional equipment. As a result, potentially better processes can be rejected at an early stage without appropriate consideration by chemical engineers, who might understand the possibilities better.

A successful approach to using PI appropriately should, therefore, involve a multi-disciplinary team in which development chemists, physical chemists and chemical engineers work together from the initiation of process development.

understanding business advantages of PI

Business advantages of PI will derive from the technical consequences of intensification; although specific to each individual process these may include:

✓ smaller and lighter equipment

Smaller equipment could imply lower cost. However, intensified equipment is likely to be more complex, thus cost per tonne will be higher than conventional equipment. Fundamentally, it is the total installed capital cost of a plant that is significant, so if equipment is smaller and lighter, the buildings and structure costs could also be considerably lower. On the other hand, control systems, storage, utilities and ancillary costs are unlikely to change significantly. So a reduction in capital costs could be achieved as a result of PI, but this is not inevitable.

✓ reduced hold-up

A smaller hold-up of valuable process materials will result in working capital reductions. However, the quantity of material held in the plant is often considerably smaller than that in storage, so working capital reductions may be small.

A reduction in hold-up of hazardous materials could also have significant safety benefits. However, it is important to appreciate that risks are reduced, not eliminated, and intensification can introduce new risks.

✓ smaller variation in process conditions

The outcome of many processes, particularly those that involve fast chemical reactions,

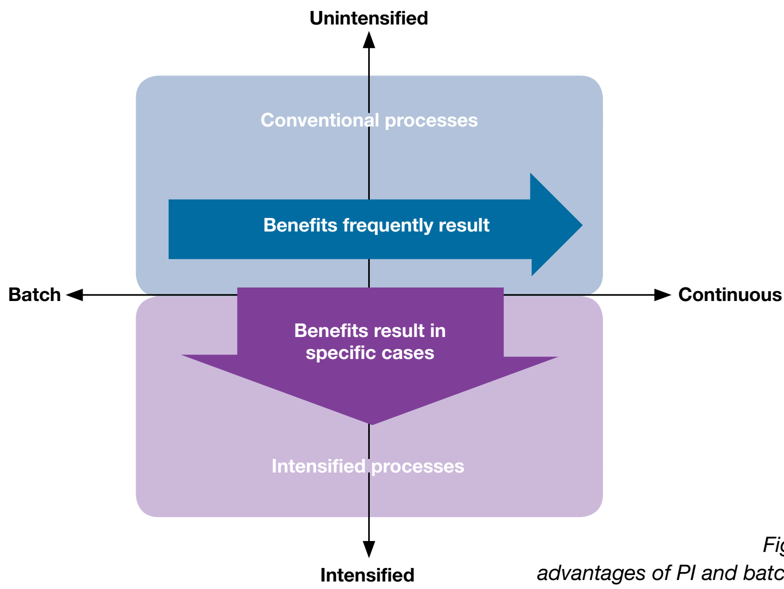


Figure 1: Business advantages of PI and batch-to-continuous

depend on conditions in localised areas within the equipment. For instance, the conditions in mixing zones, heat-transfer films and/or mass-transfer films can be critical to the selectivity of certain chemical reactions.

The economics of many processes, especially those in the high-added-value sectors, are dominated by costs of feedstocks. Thus, the step-change improvements in selectivity that can result from intensification can give large benefits to the economics of the process.

There are fewer opportunities for step-change yield improvement in the bulk process industries because reactions are already well optimised. However, if the generation of impurities that are troublesome to separate is controlled to levels that can be tolerated in the product, the reduction in separation costs could result in significant business benefit.

This effect is potentially the most significant in terms of giving a business advantage from PI.

✓ shorter residence time

In certain circumstances, extended residence times (especially those experienced in batch plants) can be detrimental to process outcomes. Shorter residence times can give lower losses to undesired by-products and impurities and, in a few cases, this can generate significant business advantage. On the other hand, if the reaction does not go to the desired conversion in a time much shorter than the current residence time, and especially if the desired and undesired processes are driven by the same factors, then reducing the residence time cannot create an advantage. If reaction temperature is increased to allow a shorter residence time, this can frequently have negative effects (see Figure 2).

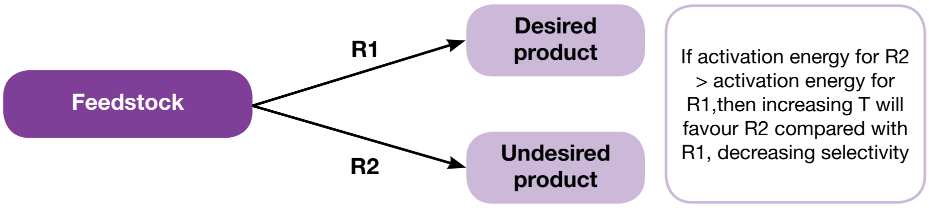
If PI involves moving from batch to continuous production then additional technical consequences could include:

✓ reduced transient demands

Transient loads on ancillary systems (scrubbers, utilities etc) can be much smaller for a continuous plant than for the equivalent batch plant. By moving from batch to continuous operation, the size and costs of ancillary equipment can be considerably reduced.

> *“only by understanding each process in terms of both its fundamental science and its business drivers can appropriate targets for PI be identified”*

Figure 2: The effect of increasing temperature to accelerate reactions controlled by the same driving forces



✓ reduced requirement for operator action

A process operating at steady state is likely to need significantly less operator intervention than a batch process. Moving to continuous operation, therefore, has the potential to reduce labour costs.

✓ replacing one large equipment item with several small specialist items

A disadvantage of moving from batch to continuous operation is the need for several items of equipment in place of a single larger item used for several operations in succession. There is also likely to be a need for more instrumentation and control equipment in a multi-operation continuous plant.

Whether the total installed cost of a batch plant versus a continuous plant is more or less expensive depends on the specifics of the process, because each process will be different.

✓ no provision for holding material for quality testing

In batch processes, end-of-reaction testing is often used to avoid the significant losses that arise from failed batches. But holding a batch for testing is potentially expensive because it extends the cycle time, thus reducing plant throughput.

In a continuous process it is much more difficult to use this sort of strategy. The alternative of providing buffer storage and provision for re-reacting incompletely-reacted material is potentially expensive and would complicate the process. Some additional costs may, therefore, be incurred in moving from batch to continuous in cases where the existing batch process needs an end-of-reaction test to confirm reaction completion.

The balance of advantages between a conventional plant and an intensified plant will depend on all of the factors outlined above. They will also be specific to both the particular process under consideration and the business environment. A process design team needs to consider the advantages and disadvantages of its particular process, together with the business context, in order to make a rational judgement about whether PI would give any significant business benefit.

a systematic approach to finding suitable targets for PI

Only by understanding each process in terms of both its fundamental science and its business drivers can appropriate targets for PI be identified. A systematic approach is, therefore, necessary to help business managers, chemists and engineers work together to understand the whole process and identify appropriate technologies, including PI solutions.

Such a systematic approach has been developed by Britest.

As a not-for-profit company, Britest's international industrial and academic member organisations collaborate to develop innovative tools and methodologies to improve process design. The methodological approach is summarised in Figure 3.

The first three stages of the methodology capture data and knowledge and translate these into 'whole process understanding'. Stages four to seven apply this understanding in order to generate better processes. The process is iterative, as information is gathered and process understanding improves.

This systematic approach ensures that opportunities for applying PI are not missed, but also that PI is not pursued in cases where it gives no tangible business benefit.

step 1: problem definition

The first stage of a Britest study is to conduct an initial screening analysis (ISA) to define the problem precisely, understand the business environment and drivers and develop technical targets to meet the business need.

step 2: analysing the whole process

The process is described using a process definition diagram (PDD) that includes information on phases present and phase changes that take place in each process task. The PDD is used as a framework to guide multi-disciplinary discussion on the process and analyse process options. The team consider whether tasks are in the most appropriate order to give the 'best' process, and whether the process could be improved by changing parameters in some of the tasks.

Whole process analysis using the PDD helps development teams identify opportunities where intensification by integration of several process tasks in the same item of equipment could give technical and/or business benefits.

step 3: developing models of key reaction tasks

Two specific Britest tools – transformation map (TM) and driving force analysis (DFA) – enable a process team to develop qualitative models of the key tasks identified in step 2. The TM is a graphical representation of the desired and undesired rate processes that occur in a process task. It is based on the standard representation that chemists use to communicate reaction mechanisms, but additionally shows:

- all known reactions that occur (including undesired side reactions);
- the stoichiometry of the reactions represented;
- phases present; and
- inter-phase mass-transfer processes.

The DFA represents rate processes and their responses to process conditions in a tabular format. Importantly, the DFA captures the unknowns and uncertainties in the process. Experimental work can then be targeted at finding the important unknown information key to the outcome of the process. The DFA table is then updated, creating a more complete and accurate model of the process task.

step 4: developing an operating strategy

The DFA table forms a useful model to predict qualitatively how the process task will respond to changes in process conditions. It also allows process teams to identify operating strategies to favour desired reactions over undesired ones that cause impurity formation and yield loss. Promising operating strategies can then be converted to potential contacting patterns.

Using the DFA table as a resource, the choice of flow- and contacting-pattern for the process can be based on standard chemical-reaction engineering practice. Once one or more concepts have been identified for the process task, proof-of-concept experiments can be carried out to confirm the analysis based on the DFA model.

In light of this work, the whole process configuration can be reconsidered, and the PDD updated to reflect the revised process concept.

step 5: defining equipment needs

Britest's duty definition and equipment specification (DuDES) methodology involves both chemists and chemical engineers in the consideration of equipment requirements.

For each process task, the team identifies what the equipment needs to deliver in order to carry out the task according to the process concept already developed in step 4. A first pass using the DuDES methodology will identify a number of 'unknowns' in terms of quantitative information that is necessary for equipment selection and design. DuDES will also generate a prioritised list of actions to fill these information gaps, so that specification of equipment requirements can be completed.

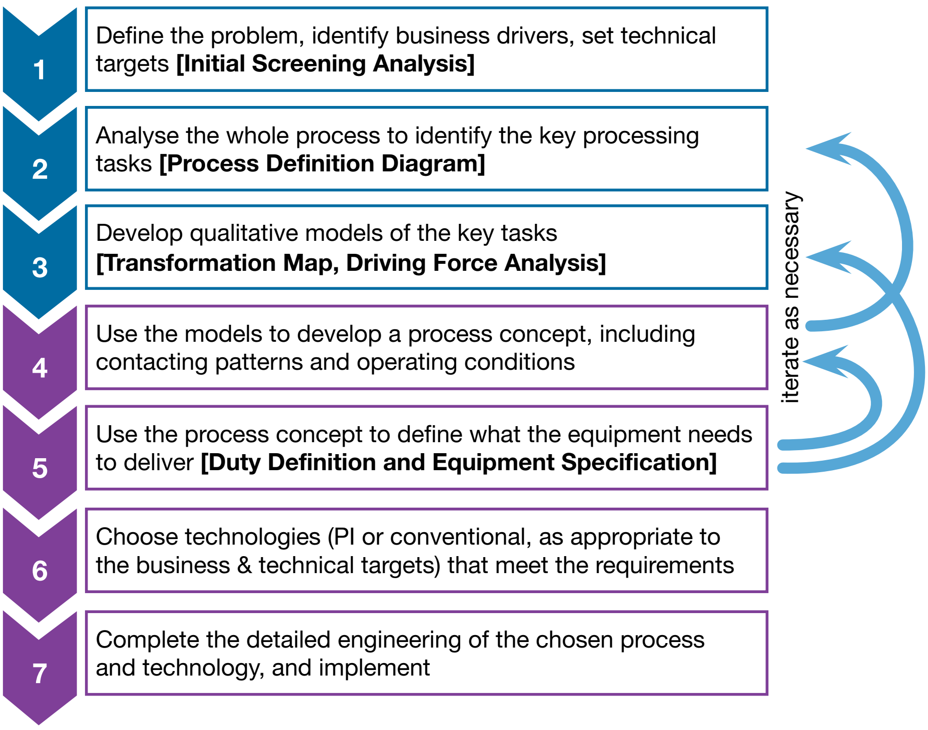


Figure 3: Britest's systematic approach to understanding the fundamental science and business drivers of a process

Credit: KIT (formerly FZK)

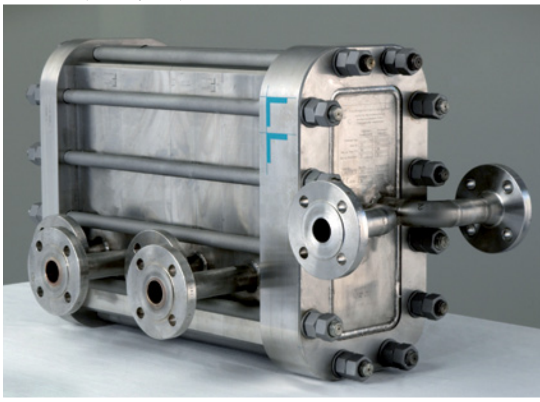


Figure 4: A production-scale microreactor designed by FZK (now KIT). In industrial use, its high heat-transfer capability gives tighter control of reaction conditions, leading to better process performance

steps 6 and 7: choosing appropriate equipment, complete the process engineering and implement

Once the team has specified the equipment requirements, equipment selection and design can be carried out using conventional chemical engineering approaches.

ensuring a solid business case for PI

There are usually very good business reasons why PI is not adopted by industry as extensively or as enthusiastically as evangelists for PI would like. It is very important for the process development team to understand the complete business case for the choice of process technology, to decide whether PI would be appropriate for the particular process and business context.

Britest's systematic approach allows a development team to address choices of technology based on the fundamental process science, without prejudice either for or against novel approaches. It helps the team generate a solid business case for new technology, if this proves to be attractive, based on a fundamental understanding of the needs of the process. **tce**

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