European Symposium on Computer Aided Process Engineering – 10
S. Pierucci (Editor)

Accounting for sustainability requirements in process design

M.P.C. Weijnen, P.M. Herder and H.D. Goel

Delft University of Technology, Department of Technology, Policy and Management,
Industry, Energy and Environment Group
P.O. Box 5015, 2600 GA Delft, The Netherlands

Abstract The incorporation of sustainability requirements in process design calls for a new process engineering paradigm, and for a new knowledge management strategy that effectively supports the development of life cycle process models in the chemical process industry.

1. INTRODUCTION

Sustainable development criteria play an increasingly important role in chemical industry decision making, i.e., from strategic, high level business decisions, down to process and plant design decisions. The urge for sustainable development of the business is concerned with the need to safeguard the long term continuity of the business:

- ensure a stable and competitive business-economic performance,
- protect the quality of the natural environment and its resources,
- ensure acceptance of the business by customers and society at large.

Business-economic motives have driven the development of the chemical industry, and economic criteria govern the decision making in all business functions of chemical companies. At the process engineering level, appropriate methods and tools are available to enable process engineers to evaluate the economic impacts of their decisions, whether it be in process design or in manufacturing operations. The business-economic dimension of sustainable development is fully internalized in all decision making processes, and embodied in a variety of assessment tools. This stage has not yet been reached for the environmental protection dimension of sustainable development. Although this challenge was recognized and accepted by the industry since the 1970'ies, its embodiment in methods and tools to support strategic and operational level decision making is still lacking. The enormous improvement in environmental performance that the chemical industry nonetheless achieved in the past decades thrived on established process engineering paradigms and practices. Structural approaches to environmental protection are still in their infancy. As the chemical industry already finds itself facing another dimension of sustainable development, concerned with the *"license to operate"*, a drastic re-alignment of business and innovation strategies is called for. In this paper we will explore how the chemical industry might develop a truly integrative, three-dimensional approach to the challenges of sustainable development, what new paradigms are emerging and how these may be embodied in new methods and decision support tools. We will focus on the design process, as this is the creative process where innovations are embodied in new plants.

2. INNOVATION SHAPING PARADIGMS

A paradigm is defined by Wei (1996) as: "*.... the whole constellation of things that defines one scientific discipline or profession and sets it apart from other disciplines...* " Paradigms shape the way we look at the world around us, and the paradigms of chemical process engineering shape the process innovation strategies in the chemical industry. Similarly, business engineering paradigms shape the business development strategies of chemical companies and their organization.

2.1. Paradigms of process engineering

The evolution of chemical process engineering starts with a pre-paradigm period, before 1915, when chemical engineering was building on empirical insights from mechanical engineering and chemistry. In 1915, Arthur D. Little introduced the concept of unit operations as *"steps common to most industrial processes, such as heat transfer, distillation, fluid flow, filtration, crushing, grinding, and crystallization"*, thus establishing the first paradigm that characterized chemical process engineering as a discipline. The empirical unit operations approach was not extended with a new paradigm until the 1960's when transport phenomena were recognized as a basic principle. This development nourished fundamental research and mathematical modeling, a development that was strongly encouraged by the surge in computing power becoming available for chemical engineers. The impact of this paradigm, that has effectively turned chemical engineering from an art into a science, is still evident from the progressive development towards higher levels of detail in the focus of R&D: from general transport phenomena, through computational fluid dynamics and to molecular modeling as present day sources of process and product innovations.

Process integration is suggested by Bogle and Perris (1998) to be the new paradigm of process engineering. The widespread adoption of heat integration since the conception of pinch technology (Linnhoff, 1982), and the promising developments of process integration towards mass exchange networks support their suggestion. Remarkable developments that can also be categorized as process integration, albeit in a much broader sense than in its original interpretation for heat exchange networks, are the integration of unit operations into hybrid systems, and process intensification.

2.2. Paradigms of business engineering

As the chemical industry developed and the scale of manufacturing operations was expanded, also the volume of waste streams expanded to a point that their processing into by-products became profitable. The business engineering paradigm of optimizing raw material efficiency through product diversification has largely shaped the complex present day petroleum refineries and the (petro)chemical industry. Until two decades ago, these complex process systems were managed by complex hierarchically structured organizations. Innovations were primarily technology driven, and markets for new products were created subsequently. Since then, the globalization of the economy, the recognition of different dynamics in the markets for different petroleum products and chemicals, and hence, the need for market driven innovation have driven the chemical process industry to a drastic re-structuring. In the present day business environment, shareholder value is on top of the priority list, urging companies towards lean and mean business-driven organizations. The *focus on core business* paradigm created the present day situation in which only a limited number of world-wide players or strategic alliances operate in each base chemical and polymer market. At the company level, the complex hierarchical organizations have been replaced by independent business units, and within these units each plant is operated as an independent profit center. Natural consequences of the business re-engineering paradigms are a focus on core competencies, a dwindling interest in general research, cross-cutting technologies and engineering skills, and a limitation of process integration efforts to an intra-plant scale. Inter-plant (site wide) process integration is virtually limited to intra-company initiatives, and is only becoming scarcer as the different plants in complex production sites are now owned and operated by different companies.

2.3. New challenges - new paradigms?

The chemical industry's response to the environmental challenge has so far been firmly rooted in the established paradigms of the process engineering profession. A variety of new unit operations was developed and added to existing plants, either to separate environmentally harmful components or to convert these into harmless substances. The fundamental insights acquired since the transport phenomena paradigm have helped to produce very sophisticated environmental technologies such as membrane separation and selective catalytic conversion technologies, and also to improve the selectivity and efficiency of separation and conversion operations in the primary process. The impact of the process integration paradigm is evident e.g., from the enormous energy efficiency improvements achieved in many companies. In spite of these achievements, however, it is felt that the industry's approach to environmental protection is more ad-hoc than structural. Although the paradigm of a structural, source-oriented approach to environmental protection has gained acceptance, it is not yet embodied in process design engineering practice. As long as suitable methods and tools are lacking, opportunities to add value to the process and create a competitive edge will be missed.

3. THE DESIGN PROCESS

A good design process starts with a correct formulation of the design problem, specifying system boundaries, design constraints, performance criteria for the design, and the design space. In the conceptual design phase, process alternatives are generated, synthesized, optimized and evaluated on the basis of the specified performance indicators. The need to consider sustainability requirements as early as in the conceptual design phase, is emphasized by the fact that decisions made at this stage typically determine 80-85% of the overall process costs (Westerberg et al., 1997).

3.1. System boundaries

The sustainability challenge forces the process designer to adopt a new perspective to the system of 'plant to be designed'. In comparison with the established practice of designing a plant as a stand-alone system, the system boundaries are significantly widened in both the dimensions of time and distance: The designer needs to take a *life span* perspective of the plant and its products, and he needs to take all possible interactions with the plant *surroundings* into account (Villermaux, 1996). The environmental perspective does not only relate to the natural environment, but may include neighboring plants that may have an interest in utility sharing, exchange of by-products, etc., thus reducing the overall environmental impact through external process integration. The life span perspective implies a cradle to grave assessment of the design, and implies that the plant must be designed for responsiveness to changes in the business environment (e.g., market, legislation) during its life span.

3.2. Constraints and performance criteria

Thus far environmental considerations are incorporated in conceptual design by treating them as *constraints* to the design problem, designated by environmental regulations and (foreseeable changes in) legislation. A structural approach to environmental protection, however, requires that environmental issues are systematically addressed as design *objectives*, to which purpose suitable environmental performance criteria must be defined. The environmental dimension of sustainable development entails more than meeting emission limits: it is about maximizing the efficiency of material, energy and water use, about the use of inherently benign substances and production methods, and about pollution prevention throughout the life span of the plant, including its demolition.

A major hurdle in applying sustainable development performance criteria is their ill-defined and qualitative nature. Even more so than for the environmental dimension, this problem is encountered in dealing with the social dimension of sustainable development. Clear definitions and indicators, both quantitative and qualitative, are needed to support the implementation of these criteria in process design. As shown by Herder (1998), project commissioner, design engineers and other experts involved in a process design need to arrive at a shared definition of design objectives in the design problem formulation stage, to be explicited in a comprehensive Basis of Design, and at a shared agreement on the hierarchy of design objectives, in order to avoid expensive re-work in later stages of the design.

3.3. Methods and tools

In industrial practice, the search process for viable process alternatives within the confines of the design space largely relies on heuristics, and the performance indicators on the basis of which the selection is currently made, are mainly economic indicators (e.g., return on investment). Besides the well-established methods to assess the economic viability of process alternatives, a limited number of methods and tools is available to support an evaluation of the ecological impact of plants and products. Especially environmental life cycle assessment (LCA) methods, originally developed for discrete products and specific materials, are gaining interest for process evaluations. Such evaluations address a wide range of emissions and their environmental effects, but cannot handle non-quantifiable environmental effects (e.g., those concerned with persistent chemicals). Other problems involved are concerned with, e.g., the ranking of alternatives, requiring an ambiguous aggregate score for each alternative.

In analogy with the environmental life span approach, also economic design evaluations are increasingly treated in a life span perspective, aimed at minimizing the so-called *total cost of ownership* or TCO (Ishii, 1997). However, the integration of environmental and economic objectives in the design of sustainable, green or clean processes is still in its infancy. Basically, the present framework of methods and tools is not able to handle design requirements that cannot be converted into costs, and requirements that are of a non-quantitative nature. Major hurdles to be taken for an integrative *sustainability performance* evaluation of technology and business alternatives, including the social dimension of the sustainability issue, are concerned with data uncertainty and ambiguity (quality of information) and the lack of systematic and objective assessment methods (quality of information processing). The quality of information and information processing challenges in a design engineering context are, in fact, problems of knowledge management.

4. KNOWLEDGE MANAGEMENT

More than data and information, knowledge is a crucial asset, also considered as the fourth production factor. The process engineering knowledge and experience embodied in the design, construction and operation of the existing process installations are recognized by the industry as a critical success factor in the competition for the future markets. Especially design engineering is a knowledge management challenge in itself, as this activity not only draws on many sources of explicit knowledge (data bases, process models, previous designs, etc.) but mainly relies on the implicit knowledge and experience of the experts involved. In spite of the extensive documentation stored on previous designs, it is estimated that only 20% of the knowledge acquired through previous designs is actually captured and reused (Westerberg et al., 1997).

4.1. Knowledge management in conceptual process design

As many design projects are cancelled along the way, most companies are hesitant to involve a large design team in the early stages of the design. Hence, the conceptual design is made by one experienced process design engineer, or a small number of designers. It is up to the designer to consult other experts in this crucial stage of the design. Quite often, however, he will find himself under tremendous time pressure and is thus not encouraged to seek information and opinions from other experts. As he relies on his experience, he is prone to making many of his design decisions implicitly, either not even realizing that he is doing so or simply not recognizing the need to explicitly document the 'why' of many of his decisions.

4.2. Knowledge management challenges in business driven organizations

In the new business organization of many companies in the process industry, the business functions of research and development, design engineering and manufacturing support have been reduced in size and redistributed over the new business units in such a way as to deliver tailor made services to their business unit. Excellent conditions have thus been created for knowledge sharing between process development, design and operation within the business units. The downside of this change is a deterioration of conditions for knowledge sharing across business units. In the present day situation of harsh international competition between lean and mean business driven organizations, attention is now focused on innovative approaches to knowledge management to ensure that lessons learned from previous projects are captured and shared between different experts, business units and business functions.

4.3. Knowledge management strategies for sustainable development

In the strategies employed by the industry to overcome the barriers to knowledge sharing, two fundamentally different approaches can be distinguished: the *actor oriented approach* and the *systems oriented approach*. In the actor oriented approach the individual professionals are fully recognized as the carriers of crucial, largely implicit, knowledge. Information and knowledge systems can support, but never replace, the professionals as the generators and carriers of the company's knowledge assets. The systems oriented approach seeks to retrieve the professionals' implicit knowledge and make it explicit, so that it can be stored independently from the professionals that created the knowledge, to be retrieved and reused when wanted. In the design engineering practice of the process industry and engineering contractors both strategies are more or less successfully employed. Within the design process, the parallel or concurrent approach can be seen as an actor-oriented approach to improving the sharing of knowledge between disciplines and between phases of the process life cycle. Between business units, knowledge sharing is achieved through skill groups, workshops etc.

An effective response to the sustainable development challenge can only be found in a balanced combination of the actor and system oriented strategies. With respect to the knowledge contents of the design process, many sources of explicit knowledge are used already, and these will only increase with the need to retrieve e.g., operational performance data and environmental impact data for process life cycle evaluations. As information collection strategies and data quality assurance are standardized, the possibilities for explicit knowledge storage, retrieval and processing will also be improved. However, even though the role of explicit knowledge systems is expected to grow, these will never be able to replace the actor oriented strategy. On the one side, there is the fact that experts are not eager to make their expert knowledge explicit and that personal communications are their preferred way of sharing knowledge. On the other side, the many ill-defined and non-quantifiable criteria that figure in process design, can only be dealt with if project commissioner, designers and other experts involved arrive at a shared understanding and interpretation of these design criteria.

5. CONCLUDING REMARKS

The search for a structural, source-oriented approach to environmental protection can be seen as a logical step following the paradigm of process integration. The models and tools to effectuate this approach are in an early stage of development. The life cycle approach is being adopted in "sustainable" process design with respect to both the economic and the environmental dimension, through TCO and environmental LCA, respectively. A promising development is the integration of both dimensions in so-called life cycle process models (Bolton and Perris, 1999). Such models can ensure the quality of the knowledge, and the quality of the knowledge processing throughout the life span of the plant. At this point in time life cycle models are not yet available, and knowledge sharing relies largely on communications between experts. The actor oriented approach to knowledge sharing will by definition remain crucial in dealing with ill-defined and qualitative design criteria. If the industry is to deal effectively with the social dimension of sustainable development, this strategy might be further developed to include external stakeholders in the design problem formulation and conceptual design stage.

REFERENCES

Bogle, D., Perris, T., CAPE and Its Roles and Benefits, Summerschool in *Innovative Process Development*, GSCE/Kemira Research Foundation, Savonlinna, Finland, August 3-5, 1998.

Bolton, L., Perris, T., *A Vision of Future Industrial Needs and Capabilities*, CEFIC/SUSTECH, PMSC, Version 1.0, July 1999.

Herder, P.M., Weijnen, M.P.C., Quality Criteria for Process Design in the Design Process - Industrial Case Studies and an Expert Panel, *Computers chem. Engng*, Vol. 22, Suppl., pp. S513-S520, 1998.

Ishii, N., Fuchino, T., Muraki, M., Life Cycle Oriented Process Synthesis at Conceptual Planning Phase, *Computers chem. Engng.*, Vol. 21, Suppl., pp. S953-S958, 1997.

Linnhoff, B., Hindmarsh, E., *Understanding Process Integration: The Pinch Design Method for Heat Exchanger Networks*, Pergamon Press Ltd., Oxford, England, 1982.

Villermaux, J., New Horizons in Chemical Engineering, *Proc. The 5th World Congress of Chemical Engineering*, July 14-18, San Diego, U.S.A., 1996.

Wei, J., A Century of Changing Paradigms in Chemical Engineering, *ChemTech* May, pp.16-18, 1996.

Westerberg, A.W., Subrahmanian, E., et al, Designing the Process Design Process, *Computers chem. Engng.*, Vol. 21, Suppl. pp.S1-S9, 1997.