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Integrated Production Systems for The Process Industries

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Introduction

The process industries encompass a diverse set of plants. These include chemical and petrochemical plants, oil-processing plants including refineries, pulp and paper plants, metallurgical plants, and pharmaceutical plants. There are large capital investments put into these plants, hence operating them efficiently is of major concern. Requirements to plant operations are, however, becoming increasingly difficult to meet. The main reasons for this are tighter quality bounds, resource awareness, higher demand on plant throughput, rapid changes in operating conditions, and the increased complexity of the plants themselves.

Product quality is strongly focussed. Hence, the width of the quality bounds will steadily decrease. This can only be met by good control of all input factors, in particular the quality of raw materials, and of the process plant itself. In addition to this, the quality bounds on effluents are governed by tight regulations due to environmental concern.

Resource awareness implies that plants must be run such that losses are minimized. Such operating conditions do not necessarily comply with straight-forward plant operations. Very often high resource efficiency implies difficult operating condition.

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In sectors with a high marked demand the production rate is important. Increasing throughput puts pressure on a system. This complicates operations. The equipment failure rate will typically increase. Increased stress will also affect the quality of operational decision-making performed by plant personel.

Flexibility in plant production implies that the same plant can produce a range of different products and that transition times are short. This again complicates operations since it is much easier to operate a plant during steady-state conditions than during transient periods. Flexibility may also mean using different types of raw materials. This is a typical issue in the metallurgical process industries when companies seek to minimize the cost of their raw materials.

Before discussing plant complexity in general, we will briefly focus on chemical plants. They will typically consist of a large number (> 100) process units such as reactor, mixing tanks, distillation columns, and heat exchangers. These unit processes are coupled by mass and energy flows as shown in Fig. 1.

The two main reasons for the increased complexity of the plants are:

- Earlier plants could be divided into sections with little or no interaction between. Typically, sections were divided by buffer tanks. Today, cost limits plants from this. This tightens the coupling between process units.
- Modern plants recirculate mass and energy to economize with input resources and minimize negative environmental effects. This introduces couplings between units. In particular, feedback loops are introduced when downstream material or energy is fed to some upstream unit, as shown from unit C to unit A in Fig. 1. Feedback loops may complicate the understanding of plant behaviour significantly.

A consequence of the tighter interaction between unit in a plant is that it is necessary to move from a unit-process oriented view to a system oriented view on plants. Thus, plant behaviour can only be inferred by some overall view on the plant.

Both technological and social development present industry with a range of possibilities to improve plant operations, ie. meet the challenge described above.

A key issue in this development is the perspective of industrial production as an interdisciplinary activity where technology and organizational studies are integrated. Despite a growing acceptance of an overall perspective, the fragmented and professional-orientation of forms of production do not always facilitate change. Traditions, cultural differences and a specialized education all produce doubtful sustenance for a comprehensive perspective.

The description above forms the starting point for this paper. Since the description is relatively general we will first limit the scope through a problem formulation. Thereafter, we will elaborate on the discipline-oriented approach to plant operations before our perspective is introduced. This is further discussed in the presentation of the INPRO-program. Before concluding we will present some of the emerging research topics.

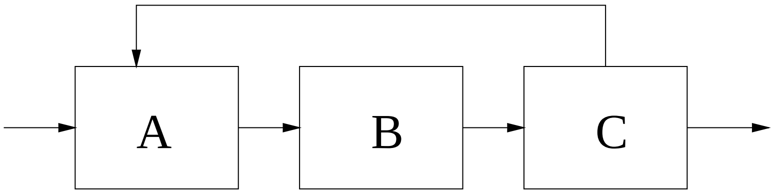

Figure 1: Simple sketch of a plant consisting of unit processes.

Problem formulation

Taking an overall view on the problem every process plant consists of three interacting components; the plant hardware such as tanks, reactor and tubes, an information and control system, and the plant operation organisation, cf. Fig.2. All three parts will influence the efficiency of plant operations, hence improvements may be invoked through all three channels. A typical measure on the plant hardware is to introduce energy recycling and new cleaning technology to reduce energy consumption and emissions, respectively. The information system can improve operations by enhanced control performance and by providing plant personnel with precise information on critical plant conditions such as product quality and emission status. Last, but not least, operations can be improved through creating arenas for organizational learning, where the diversity of experiences and competencies are utilized to identity important challenges and create new solutions.

We will define plant operations as all activities coupled to day-to-day running of a plant. Activities like maintenance, the introduction of new control schemes, and organisational development are included in this. Activities like plant design, building and commisioning, and major retrofits, however, are not included. Hence, we treat the plant hardware in Fig. 2 as a time invariant component in the overall system. Further, we will focus on the following three disciplines as a basis for improving plant operations; human resources, process technology, and control. This means that eg. the economics discipline is not represented explicitly.

We will now present a discipline-oriented approach to plant operations to clarify the priorities put onto plant operations from the human resources, process technology, and control perspective, respectively.

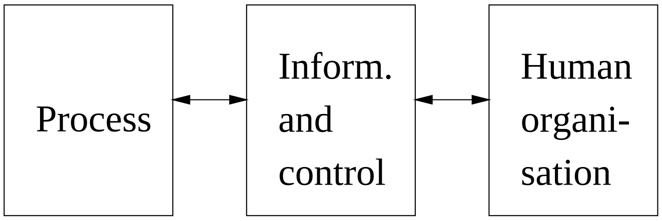

Figure 2: Overall view on the main components of a plant.

The discipline-oriented approach

The human resource perspective

When framing the human resource perspective to comply with the challenges of process plant operation, four major issues emerge. First, it is important to bring forward a socio-technical position where the coupling between technology and organizations delivers important parameters for the design of the work organization. Second, the operation of a process plant depends on the skills of the workers. Therefore it will be of great importance to understand what constitutes skills in operation of plants and how employees can acquire the necessary skills. Third, the improvement in operation of a process plant depends on the learning capabilities of the people involved in operating the plant. The organization must be designed for continuous learning. Fourth, the leadership of process plants must take leverage both for constructing a learning organization but also to manage the total complexity of available resources, ie. technological and organizational resources.

The socio-technical view is based on the fact that technology and social systems are closely linked as shown in Fig. 2. The socio-technical thinking delivers knowledge both on how to design work in a process plant and how to go about using participative approaches to the organizational change process. The major aim of a socio-technical work system is to develop working conditions encouraging the employees to use their total human resources to improve the operation of the plant. A deficiency of this perspective has been the somewhat naive view on technology.

Operating a process plant depends on the operators' and managers' skills. Formal training and education is of course very important, but recent development in theories of human knowledge and decision-making has put more focus to skills aquired through work experience (Polanyi 1983). In particular, the tacit dimension of human knowledge has received increased attention. The notion of tacit knowledge points to the fact that we as human beings know more than we are able to explain. This means that a skilled person cannot communicate to others the complete set of knowledge that constitutes the basis for his/her skills. The tacit dimension is hence very importantin in every skilled person's professional work and should eg. be accounted for in the design of training programs.

The really complex decisions are the ones involving judgement in situations where there is no clear problem formulation and no clear preference scale. These are the important decisions because they deal with not programmed activity. As such they will possibly be the tools for innovation and for solving critical operational problems. Our argument will be to take leverage both kinds of human problem solving capacity, and accept that tacit understanding can support finding solutions. The point here will be to organize human activity to support this kind of activity.

Learning is understood as the vehicle for continuous development, and the learning process can take on different forms. The simplest form is often referred as 'single loop learning' (Argyris & Schon 1978). This learning implies improving the capacity to solve the problem as it is already defined. This learning leads to perfectioning routines and tasks within a given set of values and norms. In this sense, single loop learning has limited potential in supporting innovation processes running the plant. The second type of learning is 'double-loop learning' implying a process where values and norms are challenged. This type of learning might be very important in supporting a continuing innovation process running the plant. If the main interest is to create or support learning processes aiming at continuous learning in operating the process plant, there is no doubt that it is important to design organizational practices that support double-loop learning.

Our final argument emphasizes the importance of leadership. The leadership challenge focuses on how to run the daily operation of the plant and how to prepare the plant for changing conditions. The leadership must both take leverage for how to efficiently use available resources given by the technology, human resources and economic possibilities. The other element of leadership is to be proactive preparing an organization for handling potential changes in technology, market and contextual variables.

The process technology perspective

Process Engineering disciplines have traditionally focussed on design. When the plural form 'disciplines' is used here, this signals that there is not one coherent process engineering viewpoint, but several, depending on what specialization of process engineering one is talking about. The following description will outline the two most common viewpoints, as these are currently taught to Chemical Engineers at NTH.

The classical Unit Operations oriented Chemical Engineer will focus on the design of an individual unit and the chemical / physical processes occurring in it. The design is basically oriented towards high local efficiency, such as efficient heat transfer, high thermodynamic efficiency factors, high rate of chemical conversion, etc. This kind of design requires good knowledge and understanding of the physics and chemistry involved, and the scope of the design task is usually limited to a single unit. Considerations regarding the basic control loops keeping the unit on nominal operating conditions and rejecting disturbances in the vicinity of these may be included. Higher level control objectives, as well as considerations regarding how an operating organization should run the unit, is usually not the Unit oriented process engineer's domain. He will usually not be concerned with the process as a whole.

Process Systems Engineering is another perspective, where the design and realization of individual units is less emphasized. The processing plant as an overall hardware system is here the main concern. The design of such systems is characterized by a highly modular mode of thinking: The overall function of the plant is broken down into subfunctions which may be realized through established Unit Operations, and these units are then strung together into a connected structure; the Process Flow Diagram (PFD). The process systems engineer is not concerned with the detailed design of each unit to the same extent as the Unit Operations Process Engineer. Instead, his view of the process will be on a higher level of abstraction. He may well be considered as an analog to an architect; the architect who makes the functional specifications for more detailed design to follow.

Economics and technical feasibility are two primary objectives in Process Systems Engineering: Basically, the Process Engineer will attempt to come up with the processing structure that performs the desired task at the 'best economical result'. The latter phrase is hyphenated for a reason: It should be realized that the economic models used in process systems engineering are usually quite coarse. This relates in particular to the estimation of operating costs, where one may get a reasonable estimate of cost items such as raw material and energy costs at nominal steady state operation, but where important items such as man power, down time and maintenance are treated in a very superfluous manner.

The dynamics of the entire processing plant should ideally belong to the Process Systems Engineering phase, but does often not: The study of system dynamics (and thus also the inclusion of higher level control objectives) resulting from interactions among different units in the plant have only recently become tractable, since tools (computer program systems) for dynamic modeling and simulation of entire plants have lagged severely behind their steady state counterparts. The current emergence of such tools will make it substantially easier to take the dynamics of entire processing systems into account, not only in the design stage, where one may now start seeing an emergence of integrated process and control system design: In optimization of process operations, as well as in situations where retrofits and modifications of the existing plant are considered, the ability to 'try out' a simulated change before the actual modification is made, will have a significant impact.

It is however too optimistic to assume that the existence of computerized tools alone will change the situation sufficiently: In order to be able to utilize these new tools, process engineering and control engineering will have to develop a common ground which may serve as a basis for engineers working closely together on the design and improvement of processing plants. This has educational implications.

A final issue, which has been treated lightly so far, is the simple fact that processing plants are operated by a human organization. Planners and managers are needed in order to link the external world, in terms of purchasing, marketing, sales, etc., to the internal plant environment, and operators are needed in order to ensure that the plant runs smoothly even in the case of disturbances and incidents not accounted for by the automatic control system, and usually also to bring the plant from one operating point to another. Process engineers are rarely educated in these organizational issues.

The control perspective

The control perspective on process plant operation has traditionally focussed on the design of the control and information system as the means for safe, flexible and efficient plant operation. This implies that the importance of plant design and organizational issues have been underestimated. From a control perspective, the design of the control and information system is put into a squeeze between plant design and the organization in the following sense. A plant design is delivered to the control expertise with the task of designing a control and information system which enables safe, flexible and efficient plant operation. On the other side, the organization such as operators and process engineers will in most cases interact with this process only through the control and information system. The importance of these links have been neglected, since communication with both plant designers and users, ie. the organization, has been limited. There are, however, continuing efforts in bringing plant and control design closer together both from a process technology and a control perspective. A tightly coupled plant and control design is usually denoted Integrated

Process Design, this is becoming common practice in some large chemical process companies. In much the same way, the human issue is being increasingly focussed by the control society. A major driving force in this development is the increasing awareness that one profession needs close links with other professions to enhance its impact on the problem at hand: improve process plant operation.

From a control perspective there are two major obstacles when communicating with other disciplines; understanding feedback and dynamics. Feedback, or more precisely negative feedback, is a concept nature has utilized through all times. In our body there are numerous feedback loops. These are necessary to stabilize the activity like blood pressure and temperature. This concept is penetrating deeper and deeper into the science of engineering. Viewing a modern process plant, feedback is more dominant than some years back. Striking examples of this is energy and material recirculation, such as heat integration and reuse of materials. If we include the organization and look at plant operations the use of feedback loops is quite evident.

The running of a process plant implies that a large amount of decisions are made and executed every day. There are long time-scale decisions, typically longer than one day, related to planning tasks such as production planning, maintenance planning, and purchasing plans for raw materials and energy supply. There are medium time-scale decisions directly related to plant operations. Examples are start-up and shut-down situations, transition from the production of one product type to another, and operation during process upsets or faults. An important issue in this is the ability to handle multiple constraints. This has been successfully automated by use of the model predictive control strategy in some plants. This is an on-line optimization strategy based on a simple model of the plant in question (Rawlings, Meadows & Muske 1994). Short time scale decisions, typically shorter than one hour, are performed on a massive scale. These are most often performed by a control system and involve decisions like choosing the opening position of valves, speed of conveyor bands, and the output voltage of transformers. By this it is quite obvious that decision-making during plant operations, denoted operational decision-making, involves decisions with time horizons that varies from seconds or maybe less to maybe years.

A characteristic property of operational decision-making is that it is performed repetitively, either at fixed time intervals or at variable intervals. This can be depicted as a feedback loop as shown in upper part of Fig. 3.

As an example production plans may be adjusted on a day-to-day basis based on a weekly plan and experience from operations during the last couple of days. The explanation goes as follows:

Production planning external information is available through a weekly production plan. On a day-

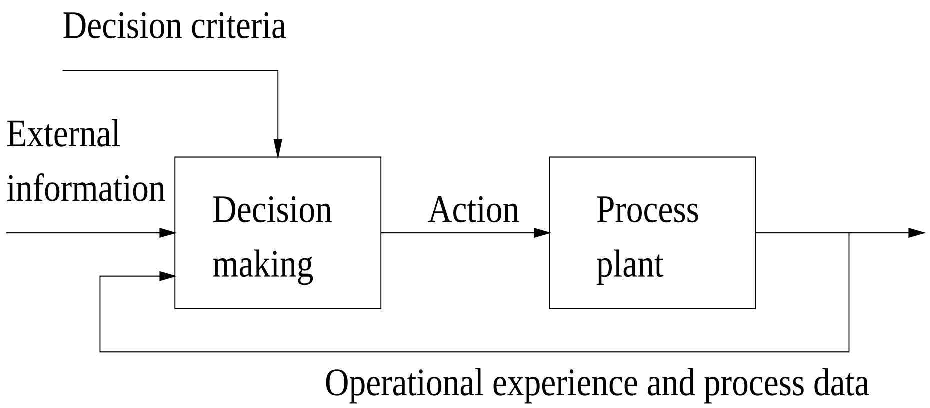

Figure 3: Repetitive decision making.

to-day basis we produce and execute production plans denoted action. During the day operational experience is obtained. This is used to possibly adjust the production plan for the next day. decision criteria are necessary to discriminate between viable possibilities. This could be guidelines on the cost of not fulfilling the weekly production plan. All repetitive decisions on large, medium and short time-scale problems can be formulated in an identical manner.

A plant consists of many subsystems operating on different time-scales. When analyzing a plant it is important to structure its description. One way of doing this is by dividing according to the time-scale of interest. This is inherent in the control perspective, since analysis of system dynamics is vital in every control design. Experience shows that it is difficult for many disciplines to understand and integrate a system dynamics thinking into their design work.

Considering the human issue is important from a control perspective since many of the loops in operational decision-making involves humans. The focus has been on man-machine interaction, ie. on displaying information. Some work has, however, been done on using ideas from cognitive science to structure decisions, cf. (Rasmussen 1986). In this context structuring means grouping decisions according to a characterisation of them, and analyzing how different types of decisions should be supported by computer-based systems.

INPRO[2]

Motivation

In the problem formulation we defined the means to improve plant operations as being the information and control system, and the plant organization, cf. Fig. 2. The discipline-oriented approaches discussed above shows that the three disciplines focus their own domain, which is natural, but also the tendency towards incorporating the views of the other disciplines. The latter is particularly true between the process technology and control view. The divide between the organisational viewpoint and technology is, however, very marked.

Taking the systems view in Fig. 2 it is obvious that an integrated approach, if feasible, is the correct approach since no one component can be singled out and changed without harmonizing other parts. This is caused by the fact that there are close two-way links between the different parts. The concept of integration is a non-controversial mainstream idea which, today, is pursued in many areas. The approach taken in the research project INPRO does, however, have certain characteristic which makes it somewhat unique. These can be summarized by:

- a true balance between the organizational and technology components. Most projects have a heavy bias to one of these sides.
- an academic research project focusing plant operation within the framework defined earlier. Traditionally operations have received little attention by academia (Rijnsdorp 1993). Broadly speaking it has been considered too practical.
- tightly involved industrial partners within the process industries. This implies that the research area is a priority field for the involved companies. Hence, they will run internal projects together with INPRO to further close interaction the academic research and application-oriented projects.

Project initiation

The project was initiated over a period of two years. Members of the research group visited several process companies. The purpose was to develop a dialogue with core employees in companies aiming at creating a mutual understanding of important research questions. All together we visited 15 companies. Every visit lasted a full day, and included discussions with the management and

[2]INPRO - INtegrated PROduction systems for the process industries

process engineers, and a tour of the production facility. From this visit three major areas of interest were developed:

- Organization development, including a redefinition of the work roles for workers and management.
- The logistics of the production system.
- Decision support systems in the production process.

The project started in the summer of 1994 and will continue until the end of 1997. In the program we have at the moment 9 participating companies, all important actors in the Norwegian process and oil industries.

The INPRO program is organized to create opportunities for extensive communication between project members to facilitate the creation of knowledge through engagement in dialogues. We expect that the professional boundary crossing in this group will be very valuable for creating a shared understanding of the operation of process plant This is accomplished by the following means:

- The students follow courses, emphasizing plant operation and system thinking, developed as an integrated part of INPRO.
- Seminars are held both at the university and in the participating companies. Examples of themes are 'Strategies for centralizing plant operations' and 'Technology transfer from research to plant operation'.
- Concrete definition of the individual research tasks which form the basis for the theses is important in the early stages in the project. A critical mechanism to obtain the integrated view on the research are discussions of concepts and research plans within the research group where all disciplines are present.

It is important to note that INPRO is organized as a doctorate research project. Hence, the theses produced must satisfy the quality measures at each participating department. This constraint is met by focusing the importance of 'staying in ones own discipline'. This means that all the graduate students have a home base, that being organisation, process technology, or control. The outset for the research is, hence, the home base. From there the research moves on to form links and joint activities.

Goals

The INPRO-program shall develop expertise and educate highly-qualified staff who are trained to focus on the integrated aspects of process companies. The main goals are:

- Educate Dr.ing. (Ph.D.) candidates with a comprehensive understanding of complex production systems.
- Develop multidisciplinary expertise to provide a knowledge bank for the Norwegian process industries.
- Develop expertise within the Norwegian process industries that can contribute to a mutually productive integration with educational and research institutions.

Organization

As mentioned INPRO started in the summer of 1994 and will continue till the end of 1997.

INPRO is steered by a board with representatives from The Norwegian Federation of Process and Manufacturing Industries (PIL), The University of Trondheim - NTH and the process industries.

At present INPRO has nine doctoral scholars engaged in the programme with backgrounds from chemical engineering, engineering cybernetics (control), and organization and work science.

Each scholar is to linked to a specific company and there is to be regular contact visits to this company throughout the period of study. These form the industrial basis of the work for the doctoral dissertation for each individual scholar.

The industrial members together with a brief comment on their main production areas are listed below:

- Hydro Aluminium Sunndal - aluminium production
- Borregaard ChemCell - chemical cellulose production
- Statoil UoP, Gullfaks - offshore oil production
- Statoil Kårstø - gas processing
- Elkem Fiskaa - ferroalloy production
- Falconbridge Nikkelverk - nickel production

- Nycomed Imaging - pharmaceutical production
- Phillips Petroleum Norge - offshore oil production
- Norske Skog Tofte Industrier - cellulose production

Research tasks

To give a flavour for the research tasks that are emerging we will, in the following, go into some details on this.

A problem that applies to the operation of process plants arises from the 24 hour a day production. While the production is continuous, the work organization is divided into shifts, supported by a daytime organization responsible for areas like maintenance and human resources. Furthermore, consequences of actions made by one shift often come into effect at a later shift. Hence, one crucial element is the communication and cooperation between the different organizations that make it possible to identify problems, take relevant actions and to transform these experiences into learning. The research will focus on communication within each shift, between shifts, and the daytime and shift organization. The main elements are

- mapping of the information and communication flows.
- identification of patterns of communication that support or inhibit learning.
- an action research strategy (Argyris & Schon 1978) that seeks to reorganize the established pattern of communication to improve learning.

Using the same motivation as above another research project will focus on the information system itself. Using batch production as the case example the goal is to establish generic knowledge on how to structure knowledge related to the plant and plant operation for this type of plants. The idea is to model the plant as a set of resources, a typical resource is a reactor, and the batches as dynamic elements that move through these batches as they are being processed. A batch, which could be defined as an object, is uniquely defined by its batch number. Information is added to the batch object as it is being processed. Furthermore, information is added to the plant resources, this can eg. be production and maintenance relevant information. The information structure should form the basis for applications like production and maintenance planning, documentation, quality assurance, and fault detection and diagnosis.

The use of model-based applications for optimization, planning, and fault detection and diagnosis is steadily increasing. One main reason for this is the fact that model-based application tend to improve plant operation. Based on this two research projects will focus on how knowledge can be transformed into models for the use in model-based applications, and how these can be efficiently used to improve plant operation. Modeling will be seen as a means of systemizing knowledge. To gain full advantage of the knowledge captured in model-based applications the organization must have the skills to utilize the new application. We aim to derive some generic knowledge on this complex topic. We will use two different industrial cases to gain experience, and hence, support our research.

Conclusion

INPRO is an academic research program focusing on plant operation in the process industries. It is characterized by a true balance between technology and organizational issues, and has a very high degree of industrial involvement.

Acknowledgements

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