Systems Thinking and A Process Control Viewpoint for Academic Administration: Toward A Learning and Continuously Improving System

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ABSTRACT

Before embarking on the subject matter, a brief introduction to my background would put the title of this paper into perspective. I spent my academic career teaching and doing research in process control. During the last ten years I have served in university administration. While engaged in academic affairs, I came to realize that I benefited significantly from my systems and process control background. In retrospect I find systems thinking useful for conceptualizing and addressing a wide range of complex issues that come up in university management. Human factor, uncertainty and difficulty of modeling university dynamics make university administration a challenging task. Despite these difficulties, I believe that systems thinking in general and process control in particular can provide helpful guidance towards transforming academic administration into a learning and continuously improving system.

RELEVANT BACKGROUND ON SYSTEMS THINKING AND LEARNING ORGANIZATIONS

In his bestseller book, "The Fifth Discipline", Peter M. Senge defines learning organizations as "organizations where people continually expand their capacity to create the results they truly desire, where new and expansive patterns of thinking are nurtured, where collective aspiration is set free, and where people are continually learning how to learn together". According to Peter Drucker the learning organization is the organization of the future [Flood, 1999]. Many companies try to build systems that support organizational learning. For example Nevis et al [1995] presents learning models by studying and presenting examples from Motorola, Mutual Investment Corporation, Electricité de France, and Fiat.

Learning in organizations means continuous testing of experience i.e. taking action, observing its consequences, and transforming that experience into shared knowledge that is relevant to the core values of the organization [Senge et al, 1994]. It is through this *feedback* that organizations learn and improve themselves continuously. Learning organizations are committed to quality and knowledge management. As a result, they manage change more effectively and most of the time they lead the competition.

Therefore there is an ongoing interest and debate among academics, administrators and students on how universities should benefit from learning organizations. It is believed that academic institutions can employ some of the organizational learning methodologies to establish new patterns of thinking and a culture change to create a better future for themselves [White and Weathersby, 2005]. Although transforming a university into a complete learning organization may be a grand challenge, some of the approaches that render success to learning organizations may be adapted to academic administration, as we will see in this paper.

In engineering, complementary "component technologies" are brought together to innovate a product. Similarly in a learning organization certain "disciplines" must come together like "components" to innovate that organization. According to Peter. M. Senge five disciplines that are central to a learning organization are: personal mastery, mental models, shared vision, team learning and systems thinking. The body of knowledge and techniques contained in these disciplines have to be learned and practiced in order to develop the required patterns in human behavior and reasoning. Learning organizations distingush themselves from "controlling or authoritative organizations" by mastering these disciplines [Senge et al, 1994].

It is noteworthy that Peter Senge quotes *systems thinking* as the cornerstone or the fifth discipline that integrates the other disciplines into a whole. This is consistent with one of the guiding principles behind learning organizations: *the primacy of the whole* i.e. the wholes and the relationships are more fundamental than parts. *Systems thinking* is often regarded as a language to help conceptualize complex issues and help organizations to achieve change. *Systems thinking* helps people to look at organizations as a whole, analyze the interrelations among different parts of the organizations, develop learning strategies, identify patterns of behavior and develop continuous improvement plans. Galbraith [1999] shows with examples that there is a need for more *systems thinking* in management of higher education processes which are characterized by complex interactions of delayed multiple feedback loops.

In the rest of the paper we will view university as a potential learning organization and focus on its academic administration. *Systems thinking* will prevail in our approach as well. Specifically, within the discipline of systems thinking, we will explore how *process control* can provide a scientific framework for administration of academic processes.

RELEVANT BACKGROUND ON PROCESS CONTROL

A background on process control is necessary to be able to establish its similarities with academic administration in universities. After introducing some working definitions, we will dwell on two specific topics: *hierarchical control* and *model predictive control*. These are chosen because they provide useful system dynamics and control concepts and architectures to support organizational learning and to perform continuous improvement in a university setting.

Process refers to the dynamical system under consideration and consists of physical, chemical and biological operations that convert raw materials and energy into useful products. Having defined the process, it is important to classify its variables for process control purposes. Basically any process has two classes of process variables i.e. inputs and outputs. Inputs are further categorized as disturbances and control inputs. Disturbances are adjusted by nature (outside our control) and control inputs are those inputs that a decision maker can adjust or manipulate at will. Outputs are the process variables that are affected by inputs (see Figure 1).

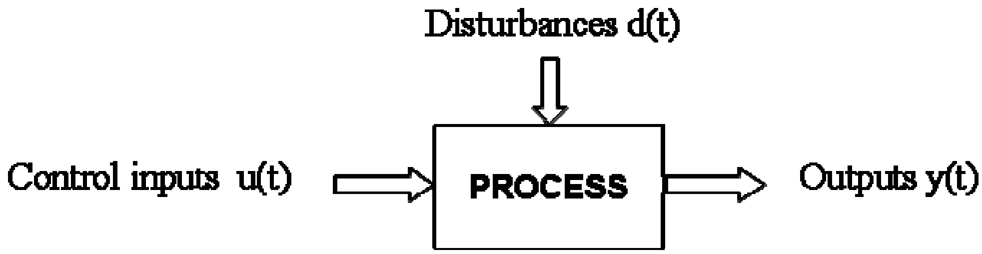

Figure 1. Process and classification of its variables.

Process control is an interdisciplinary field that studies synthesis of control structures and design of control systems to shape the dynamic behavior of a process. The most basic process control mechanism is negative feedback control as shown in Figure 2. The controller or decision maker adjusts the control input (decision) $u(t)$ to drive the error $e(t)$ between the measured output $y(t)$ and its desired target (set-point) value y^{sp} to zero. Anything we do not know about the process and its interaction with the environment is called uncertainty (unknown). Through measurement and feedback, the controller learns the uncertainty and compensates for its adverse effect on the output. Like in learning organizations, the feedback mechanism provides continuous learning and improvement of the output.

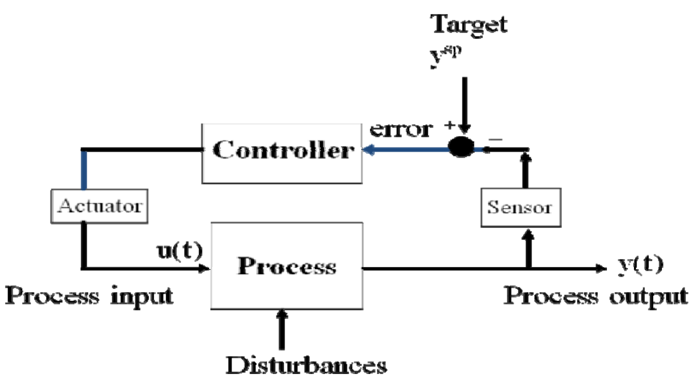

Figure 2. Feedback control.

Hierarchical Control

Most of the time, processes constitute complex and large scale systems. For example in a chemical plant a large number of process units interact through mass and energy integration involving complex dynamic interactions among many inputs and outputs (see Figure 3). In order for a process to be complex, it does not have to be physically big either. A cell in our body with its complex metabolic networks is a typical example acting like a small "chemical plant". Control of large scale systems is a challenge and has been the subject of many studies in the literature under plant-wide control. Most of the proposed approaches entail systems approach and hierarchical control concepts such as decomposition and coordination to tackle complexity [Morari et al., 1980]. Hierarchical control originates from *systems thinking* where individual parts (subsystems) are controlled in a coordinated fashion to achieve the objectives of the whole (plant). The first decomposition is done at the process level as shown in Figure 3 where the process is partitioned into its interacting subsystems. Decomposition is guided by the necessity to control the subsystems as independently as possible via decentralized controllers. Thus most process decomposition methods seek to minimize subsystem interactions.

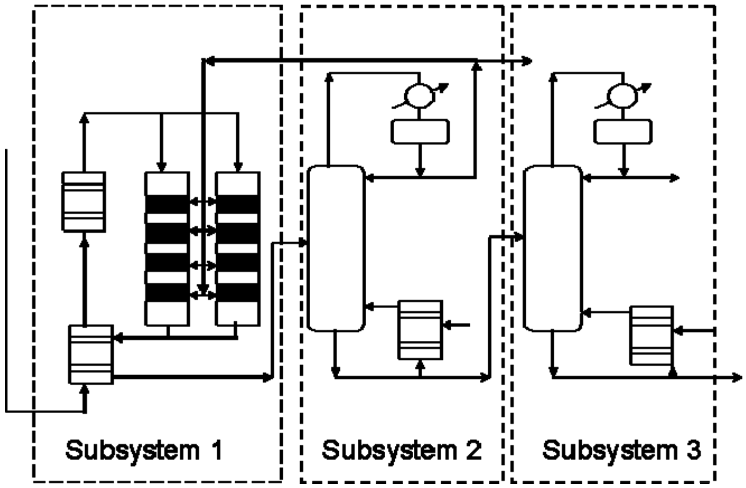

Figure 3. Process decomposition: Horizontal hierarchy

Second decomposition is done to classify and organize the different control tasks for each subsystem as shown in Figure 4. Control tasks are divided into regulation and optimization and they are implemented at different time-scales. Frequency of decision making and process intervention decreases as one goes up in this vertical hierarchy. For example regulation may be exercised as frequently as possible (seconds-minutes) by feedback controllers while optimization may be performed to update the targets (set-points) as needed (hrs-days). Vertical decomposition makes the delegation of responsibilities clear among the different decision makers. Optimizer determines the targets, and regulatory controllers keep the outputs at those targets. Information exchange between the two layers exists through feedback where optimization monitors the achieved values of outputs and compares them with their targets.

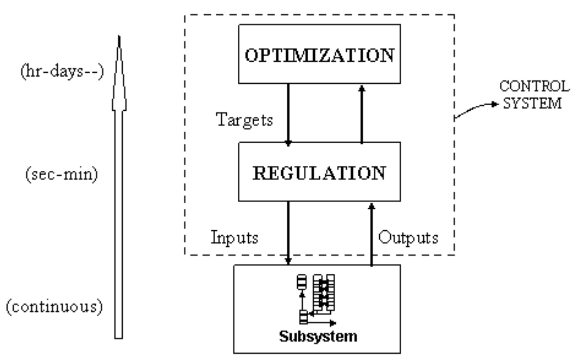

Figure 4. Decomposition of control tasks: Vertical hierarchy.

Although models and algorithms used to implement the control tasks may vary from plant to plant, most chemical plants today operate with a combination of these two hierarchies as shown in Figure 5. Decisions of decentralized subsystem controllers are coordinated to achieve the overall plant objectives. How to select the subsystems, design of regulatory and optimizing structures for each subsystem and developing feed forward/feedback information sharing strategies among the decentralized subsystem controllers have been studied in the past and they are still open research issues [Lesser, 1999; Tatara et al. 2006].

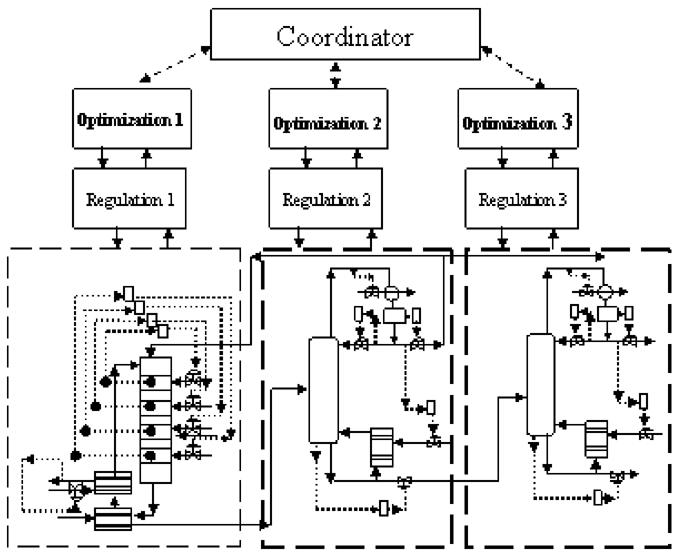

Figure 5. Hierarchical Control

Model Predictive Control

Chemical processes are nonlinear systems and they exhibit complex dynamics. They are not easy to characterize and they operate in an uncertain environment. Since its inception in 1979, Model Predictive Control (MPC) is the most successful and widely accepted industrial advanced process control technology today [Qin and Badgwell, 2003]. It may be implemented for a specific process unit or for the whole plant in a hierarchical setting providing both regulation and optimization. MPC's success can be attributed to the fact that it tries to handle many difficulties encountered in practice which include time delays, process constraints, and multivariable interactions. In addition it provides a general framework to make use of process knowledge in the form of models to control the process. Finally it allows different and changing process objectives to be optimized over time as they become integral part of the process operation.

The "internal model principle" (i.e. a description of the process must be inherent to the controller if it is to be controlled) is at the core of MPC. As shown in Figure 6, the basic idea is to make use of an approximate dynamic model of the process in real time. Using this model the output is predicted and control inputs are optimally computed to keep the predicted output at the desired target (set-point). External disturbances and the mismatch between the process and model make up the uncertainty which is learned through feedback. Feedback measurements are used to update the state of the system, and if necessary, the dynamic model can be updated on-line as well as new process knowledge becomes available. Thus MPC is a learning system that keeps up with the changing process requirements. MPC design involves two tasks: modeling and input calculation.

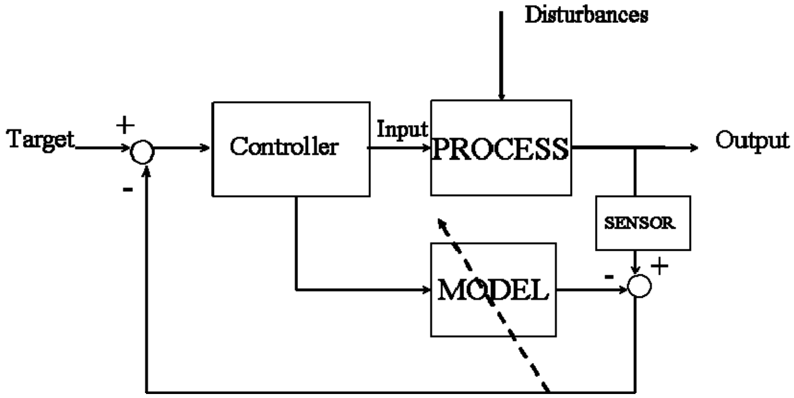

Figure 6. Model Predictive Control

MPC uses a dynamic model that relates the outputs to inputs. Accumulated valuable knowledge about the process is captured in these models. Models can be nonlinear in the form of differential equations derived from first principles or they can be empirical time-series models identified from input-output data. When such quantitative models are not available, different types of “qualitative” or semi-quantitative models can be used to describe and control the system [Kuipers, 1994; Bakshi and Stephanopoulos, 1995]. As one learns more about the behavior of the process through experimentation, process models are updated and refined if necessary.

Optimal inputs to the process (i.e. decisions) are computed by a constrained optimization which minimizes the difference between the desired setpoint and the predicted future values of the output over a specified time horizon of length P (see Figure 7). Constraints on inputs and outputs which are common in process control are included in the optimization formulation. Among the computed future control inputs only the first one $u(k)$ is implemented and the optimization is repeated at the next sample after new measurements are obtained. This way *feedback learning* is established and optimal decisions are taken with the most recent and relevant information. Because optimization is advanced in time and repeated after each learning step, it is appropriate to call MPC *moving horizon learning control.*

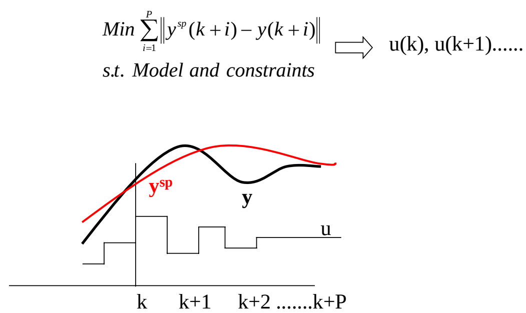

Figure 7. MPC optimization.

UNIVERSITY AND ACADEMIC ADMINISTRATION

In this section I would like to address the following question: Can systems thinking and process control play a useful role for management of human organizations such as universities? I will address this question by paralleling the aforementioned process control concepts and methods with their counterparts in the academic world.

Academic Processes

Administration of academic affairs in universities bears many similarities to what I have already discussed under learning organizations and process control. Starting from the very basics, the main academic processes of universities are education and research as shown in Figure 8.

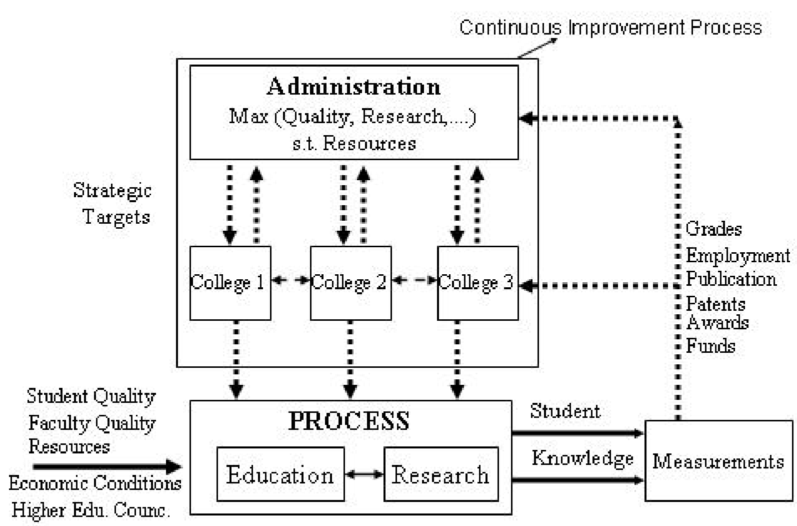

Figure 8. Hierarchical Academic Administration

Education and research have their own sub-processes and dynamics, and they also closely interact with each other. Therefore one needs to look at them as a whole system. Often research leads education i.e. research developments affecting a profession eventually find their way into classroom, and good education is essential for lasting research. Universities differ in their education and research missions; thus, they place different emphasis on “control” of these interacting processes. Nevertheless maintaining the right balance between the dynamics and outcomes of education and research in compliance with the university mission is one of the key factors for success.

Classification of Process Variables

Next we classify the pertinent variables for the process i.e. for education and research. The important process outputs are students that we graduate and new knowledge we generate. These outputs are affected by inputs such as quality of incoming students, new faculty, resources (state, federal, endowment etc.), economic conditions and government organizations such as higher education councils that may be involved in the academic governance of universities. These variables are most of the time outside of our direct control; thus, they act as disturbances. Economic crisis can decrease the number of high quality tuition paying students; changes in the University entrance exams initiated by the Higher Educational Council can shift the profile of freshmen in countries like Turkey where students are admitted through a central exam. Student and faculty quality can be indirectly influenced through better recruiting, but there is still uncertainty involved in their quality which may adversely affect the academic processes (i.e. education and research) and the best way to combat uncertainty is via feedback control which is discussed next.

Learning and Feedback Control

Like in any feedback control system it is crucial to be able to assess product quality and performance correctly. Here we are faced with the similar questions we encounter in process control: What are the best metrics to judge product quality? How frequently can we take measurements?

In a university setting it is possible to monitor the outputs by using different measurements (see Figure 8). Typically grades, awards, employability reflect the quality of students. Similarly publications, patents, awards, impact reflect the quality of knowledge produced. Timely measurement (i.e. sampling rate) is very critical for effective learning and feedback correction. For example at Koç University freshman year is an important period where most students go through academic and social adjustment. Therefore their progress must be closely monitored. As part of our freshman advising system, faculty members are required to report the student grades on assignments, quizzes, tests, labs, attendance etc. almost on a continuous basis, as they become available. This is done over the web using our monitoring system KUAIS (Koç University Academic Information System). These timely measurements taken during the course of the semester make close supervision and improvement of student performance possible.

For the hierarchical organization of academic administration, it is appropriate to replace the regulation layer in process control (see Figure 4) with the colleges as shown in Figure 8. Colleges are the learning and acting agents in universities. Their main objective is to maintain their outputs (students and knowledge) at their strategic targets in terms of both quality and quantity. Colleges learn from past experiences and implement their decisions or control actions with the help of their faculty members. Here the familiar "process control question" presents itself within a different context: What are the most significant control inputs that can be adjusted to influence of education and research processes?

Changes in the curriculum (e.g. course content, credit hours), establishing new programs, class sizes, faculty-student ratio, advising, teaching workshops, faculty teaching loads, recruiting effort, rewarding faculty and students, increasing resources and research support are some of the many possible control inputs that can be manipulated at the colleges level. Colleges operate in a constrained environment where these control inputs are limited by available resources. These resource constraints are defined through the course of strategic planning and annual budgeting which are jointly performed with the central administration. Therefore selection of the right control input depends on both the particular effect one wants to realize (e.g. education vs. research) and its implementation cost. The situation is analogous to some of the process control problems where output performance is limited by hard or soft constraints placed on control inputs.

Is Model Predictive Control feasible or is it a dream?

In order for colleges to implement the right control action they need to know (model) the effects of the above control inputs on education and research. As in learning organizations, this is often done by continuous testing of past experience since there are no mechanistic first principles models for education and research processes. One has to be ready for more "qualitative" models expressing trends, patterns and order-of-magnitude relationships, all learned from past experiences. If historical data are available, cause-and-effect models can be developed and used in a model predictive control environment which can prove to be useful. For example, close inspection of past grades of a student is often a good predictor of future performance. Such student data bases and correlations among different performances in related courses can be used to predict future performance and to help students in the selection of their course load accordingly. In our university we develop and use such models to guide our decisions. Following the trends in a student's progress from day one to graduation, establishing patterns among different course performances, taking corrective action and observing its consequences on a semester basis can provide timely learning data to correct the actions. A good advising and a monitoring system are essential for the implementation. Our knowledge bank KUAIS is used for this purpose.

In academic institutions performance monitoring and control is more challenging since it addresses human behavior and reasoning (e.g. student's attitude and response) which influence strongly the quality of any achievable improvement in performance. Nevertheless through handling of a myriad of cases, certain patterns (both in human behavior and performance) and scenarios can be established; faculty members and administrators learn from these experiences and a useful knowledge base is established for future references. It is essential to acquire, update and share this knowledge among all decision makers within and across colleges to promote team learning.

There is a need for reliable and more formal models to simulate and predict the academic processes (i.e. educational and research aspects) in universities. Some universities try to develop and use their local dynamic models. One such attempt is given in Barlas and

Diker (2000) where an interactive dynamic simulation model is developed and validated using the historical patterns of academic variables such as student-faculty ratio, teaching and research productivity. The model is used in a simulation game to support strategic decision making in university management. Galbraith (1998) constructs conceptual models with negative and positive feedback loops to describe the dynamics of student enrolments and allocation of resources to faculty based on research productivity. When such valuable systems dynamics models are available, MPC provides a powerful framework for faculty and administration to use them for decision making and continuous improvement.

Optimizing Control and Strategic Planning

So far we have discussed the first two levels of the academic hierarchy i.e. the process and the colleges. The academic process consisted of two parts: education and research. Regulation found its useful place in colleges in the form of continuous learning and feedback. The next level up in process control hierarchy is optimization (see Figure 4). For a university this third level can be viewed as the central administration (e.g. President, Vice-Presidents) as shown in Figure 8. The main goal of administration is optimizing control i.e. it defines the strategic targets for the university and implements them by working closely with the colleges. In this respect for universities it is more meaningful to consider the optimization and regulation levels (or administration and colleges) as one integrated Continuous Improvement Process (CIP). Universities must have their CIP in place to be able to implement, monitor and improve their strategic plans. In line with CIP, European University Association (EUA) argues that institutions must have a capacity for long-term strategic planning in order to improve quality in a meaningful way [EUA, 2005]. Similarly many other organizations such as Accreditation Board for Engineering and Technology (ABET), and The International Network for Quality Assurance Agencies in Higher Education (INQAAHE) have identified quality assurance as a top priority for universities.

Strategic plans involve optimization to balance different objectives (e.g. maximize quality, quantity, minimize cost) with available resources. Information exchange and coordination among the colleges and the upper administration is absolutely necessary to develop and implement the strategic plan in an efficient way. This is illustrated in Figure 8 with the two-way information flow between the colleges and administration blocks. In the absence of such communication, conflicts between administration and colleges arise and strategic actions go unimplemented. This is also observed in process control if optimization provides targets (set-points) that regulatory controllers are not able to implement due to unrecognized limitations in process dynamics or controllers.

University strategic plans are usually prepared for a future time window e.g. 5 years. But the established targets are implemented by the colleges on a yearly basis. At the end of the year the plan should be revisited and improved based on what administration and colleges learn from the actual performance achieved at the end of that year. Actual performance is based on the measured performance of the outputs (students and knowledge) plus the finances. Strategic plan development and its “real-time” implementation is exactly MPC or moving horizon control in action. In fact strategic plans are useful only if they are continuously improved in this fashion rather than as one-shot open-loop policies without feedback learning and correction.

Centralized versus Decentralized

Decomposition of control tasks into learning, feedback and continuous improvement and allocation of these responsibilities to the appropriate decision makers (colleges and administration) avoids a completely centralized management.

Decomposition into subsystems in the form of colleges is inherent to the structure of universities, similar to the hierarchies presented for plant-wide control. The degree of decentralized learning and feedback by colleges, and coordination between the colleges and the administration is a key factor in the planning and operation of academic affairs just as in the plant operations. Naturally every academic unit is expected to have its own objectives, its own dynamics but their strategic plans and actions must be consistent with the vision of the university as a whole. Thus the picture is similar to coordinated control of chemical plants. Universities must clearly define the objectives of their individual subsystems (colleges in this case) and have the necessary mechanisms in place for team learning and coordination. For example in many places Deans Council provides one such mechanism for information exchange and coordination at the level of colleges and Academic Council or Senate acts similarly at the university level.

CONCLUSIONS

Conceptualizing and performing academic administration in a flexible framework that is based on scientific foundation would offer significant advantages. This short note is an attempt to demonstrate that systems thinking and process control comes close to the realization of such an idealized framework. Academic administration can be cast into a hierarchical control setting and many process control concepts provide useful insight into the operation and management of academic processes. Such a scientific approach develops and retains the institutional knowledge better; it offers guidance to all decision makers involved; and it helps the universities to become learning organizations that can control their transformations. In addition maintaining learning and continuous improvement at a systems level provides continuity when individuals change in administration.

Quality control in education and research has always been among the essential missions of universities. More recent quality assurance programs (e.g. Bologna process) place greater demands on quality control. In retrospect the framework offered by process control can be useful to many university administrators. Different universities can incorporate their own culture and local models into such a general framework and operate accordingly.

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