Dedicated to
Professor Jakub Gutenbaum
on his 70th birthday

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Hierarchical control structures

by

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Abstract: Control of complex systems, where many detailed decisions are to be made on a current basis, along with long-term considerations, calls for structures composed of a multitude of decision units. This, in turn, may lead to various conflicts. The latter are to be predicted and counteracted by appropriate measures in the design of decision structure as well as in the course of its operation. Allocation of information and the language of communication between various levels of the hierarchy also are of the prime importance.

Keywords: control, complex systems, hierarchical structures, conflicts, coordination.

1. Origins and justification

Roughly 40 years ago, a development has started in the area of control science and engineering in search of rational answers to the following question:

- how is a control structure, i.e., an arrangement of control units and their interconnections, to be shaped and designed in order to influence – in a satisfactory manner – the processes that take place in a complex system?

Situation must be considered where we have to deal with a large number of control (decision) variables, where there is a need for continuous or almost continuous intervention, and, at the same time, a long time horizon has to be considered. In particular, this is true when economic phenomena, changes in the environment, investments, etc. are of significance.

A control structure or an organization is therefore of interest where many detailed decisions are to be made within relatively small units of time in order to assure the desired current operation of the system, but where long-term or medium-term considerations are also indispensable.

The necessity to analyze complex systems is, perhaps, one of the characteristics of our time. We encounter this necessity in a variety of areas, such as, among others, in manufacturing and production systems, energy supply, communication networks, large company management, and environment protection, to mention only a few.

The necessity I am emphasizing is strengthened by the modern capabilities of gathering, evaluating and processing information. From this standpoint, there is almost no limit to the size of the system we want to control.

Let us, however, return to the original statement of the problem: there is a need to make, in parallel and simultaneously, a great number of decisions with a long time perspective. How is this to be accomplished?

To incorporate all of it in a big computer within one large program that would know all about everything and would make (or prepare) all decisions, would certainly be contrary to common sense for several reasons, two of which I would like to present here.

First, a given intervention intended to correct the current operation usually does not have to make use of the observation of processes in the whole system. Instead, it may be based only on the observation of some part of the system. Therefore, it is possible and appropriate to introduce local decision units and grant them authority over the corresponding shares of the system decisions. In this way, the information delays and control vulnerability, that could otherwise constitute a weakness of an overly centralized structure are eliminated .

Second, one should be aware of the fact that the long-term decisions concerning a complex system usually cannot be formalized to such a degree as to be uniquely determined or suggested by the computer. In practice, it means that, at higher levels of the control structure, there is a need for decision mechanisms which employ human judgment and intuition, as it is only a human being who may possess the ability to weigh values and factors that cannot be quantified, as well as to assess and undertake the risk. Most importantly, it is only a human being who can assume the responsibility for his or her decisions. The decision ability of any person is, however, limited: he or she is unable to make too many decisions in a given time period.

What we have just said contains an essential indication for shaping a hierarchical control or a decision structure: one should take care that, at higher levels of the structure, both the number and the frequency of decisions be reduced – the more so the more complex and requiring deeper reflection the decision problem is at that level.

It is perhaps redundant to say that all this does not eliminate the use, at any place in a hierarchical structure, of computers and their software. These should implement control at lower levels where, for instance, a desired behaviour of the technological process is to be assured, or they should serve as decision support tools at higher levels. The computer offers the speed of information processing as well as efficient analysis of many options in a short time, whereby a human being does the evaluation and assumes responsibility for (essential) decisions.

Consequently, there are differences in the frequency of intervention by decision units of various levels in the case of almost every hierarchical structure (the higher levels intervene less frequently). also there are differences in the time horizon considered while making a decision (it is increasing as we go up the hierarchy). Always, and this is an important feature, the decision unit placed at the top has the authority over the whole system, and it is considering the long time interval of the system operation, appropriate from an overall point of view.

Adopting a time horizon which is appropriate, for the decision in question (i.e., for a given level within the decision structure) is a problem in itself, and it is one of a considerable practical importance. In this connection, one should mention a subtle point which can easily be overlooked. Namely, the horizon of the decision taken at a particular instant of time should reach as far into the future as the consequences of that decision could reach. If, for example, we make a decision about releasing the water from a large retention reservoir, then the perspective of all the rainfall, runoff and possible flood period must be taken into account. The fact that a subsequent, new decision will be taken within a few hours does not eliminate the necessity to maintain this kind of approach (and this is the subtlety we wished to point out). We are not permitted to create consciously, for that decision, a situation that is less favourable for the whole process than possible.

I do not want to say that the perspective of a future correction of the system behaviour by means of the next decision plays no role in determining the previous course of action. However, this is related to the risk assessment rather than to the time horizon. Our current decision may be less hedged against uncertainties when we know that a correction is possible within a short period of time.

Now, having presented the origins and general features of hierarchical control structures, I would like to highlight two of their most characteristic attributes, namely, the conflicts among decision units and differentiation of information as needed at various levels.

2. Conflicts and coordination

We have stated and agreed that control of a large and complex system by means of a single (central) decision unit is not rational or may even be impossible, if it should mean making all the necessary and current decisions.

A multitude of decision units acting within a common system may, however, lead to various conflicts.

Fig. 1 presents schematically a hierarchical structure and may serve to indicate that conflicting interests can show up between local decision units, i.e., within one level of the structure, as well as between the levels, e.g., between local units and the top unit. In turn, there is a possibility of disagreement be-

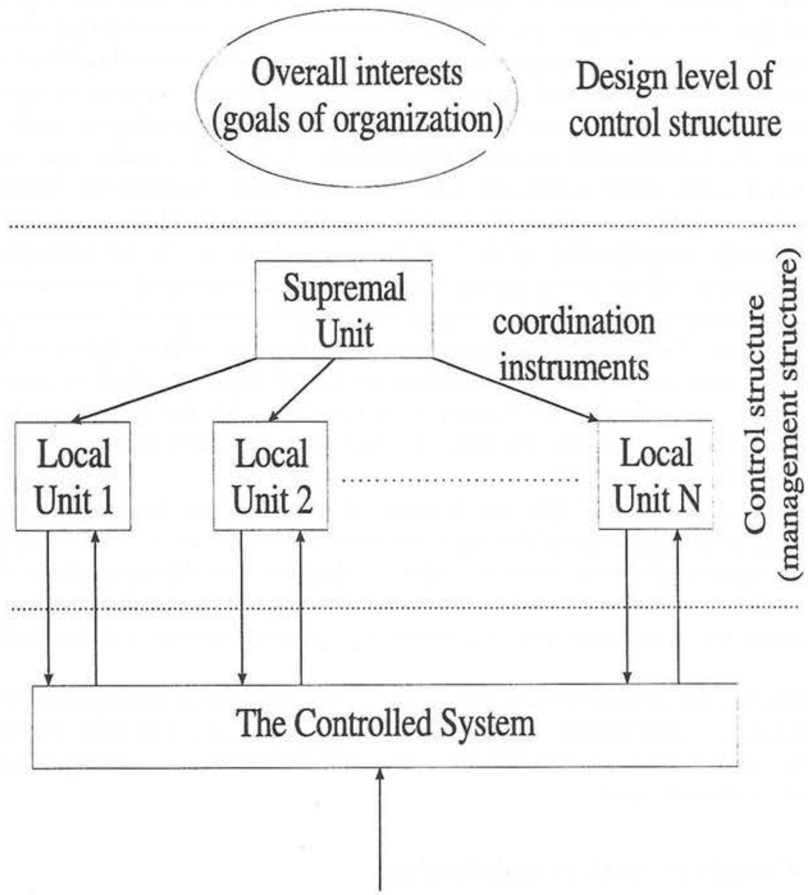

Figure 1. Hierarchical control (decision) structure (Findeisen, 1986).

tween the overall interests, that is, between the goals of the organization and the intrinsic interests of the supreme decision maker, who is in charge of the actual system operation.

The designer of decision structure and, thereafter the person responsible for functioning of the whole and for the pursuit of overall goals must be able to predict those conflicts and to have the counteractive measures at his or her disposal.

Let us make it clear that the conflicts may not exist. Namely, this is the case, when every decision unit (excluding, perhaps, the topmost one) has agreed to act in strict accordance with the laws and prescriptions that were set a priori from the point of view of the system as a whole. In control theory, we speak of the so called "decision rules". When they are introduced and implemented, it is not important any more whether this implementation is entrusted to a computer or to a human being, referred to – in this role – as "an operator" rather than "a decision maker".

The setting or design of decision rules for a complex system, subject to environment changes which are uknown a priori, is a difficult task. One should have at one's disposal an exact knowledge of the controlled system itself, as well as of the whole palette and range of external circumstances, thus being able to pre-determine appropriate actions. In practice, decision rules are usually conservative in the sense that they give priority to system stability (that is, to a security of operation), rather than to exploration of all its capabilities. Such an approach may be appropriate, however, in the case of an electric power system, but less – or not at all — advisable for an enterprise, where its very survival may depend on economic yields and effects.

In a majority of systems that are nowadays subject of study and interest, more can be obtained when the lower level decision units are left free to make the detailed decisions. We set the goals and impose constraints on these units, but refrain from prescribing them the strict rules of behaviour.

Local goals, for instance the profits achieved by each of the divisions composing one enterprise, will usually be in conflict. It is true that the profit of the firm will be the sum of the divisional profits, providing for a nice picture, but a local decision maker can gain more when acting without concern for the whole. In a coupled system, these local decision makers are in a multi-person game with each other: my profit depends not only on my decisions, but also on the decisions of other, parallel decision units.

A game-like behaviour of the local decision units may be detrimental – or even fatal – to the system as a whole, should the game have no stable equilibrium point. There is a need for intervention, that is for a supreme influence on the local decision units, with two aims in view: to neutralize the conflict, i.e., to eliminate the competitive game between the parts of the system, and to assure that the autonomous decisions of the local units would best serve the global goals and interests.

In control theory, the intervention we are talking about would be referred to as "coordination". Various instruments, i.e., the variables by means of which we would influence the local decisions, may be used, as well as various principles of operation of the coordinating unit. We know, for example, that in a situation called "goal consistency" the coordination may lead to local decisions fully promoting the global interests, i.e., no better decisions would be made by the coordinator himself.

Depending on the choice of coordination instruments, there will be a different scope of information needed by the coordinator, and different sensitivity of his action to a distortion of this information – a distortion that may bring measurable profits to local units, the suppliers of information.

The essential fact, namely that the local interests are in conflict with each other, remains. Coordination cannot make this conflict vanish – it can only neutralize it, i.e., it may prevent the conflict from showing up in the system performance. Among other things, it means that, if the coordination is insufficient or in some other way defective, then the functioning of the system may be disturbed by the game between the local decision makers.

The danger we just mentioned should not cause us to resign from the introduction of local decision units into a complex system. The local decision maker is in a position to know more about the part of the system entrusted to his care, to understand it better and to know better its actual environment. Therefore, he can make more appropriate decisions. The control theory suggests that the local decision maker is not only able to decide (being competent enough), but that he can make, under given circumstances, better decisions than a central unit. This applies, in particular, to decisions which are subject to various kinds of uncertainty, risks and constraints.

3. Information and the language of communication

It seems to be a matter of course that the decision units, acting at various levels of a hierarchical decision structure, need information of various kind and scope. Automatic control devices that take care of temperatures or pressures in a technological process make use of the information concerning physical phenomena, which is usually supplied continuously or almost continuously. A similar kind of continuous information is used by the pilot of an aircraft, who, on the other hand, is a part of an airline enterprise. A different kind of information will be needed at a higher level, where, for example, a smooth flow of production or of airline services is being assured, or – still higher – where matching of the system operation to the market demand is considered.

Fig. 2 illustrates schematically what we were just trying to say, on an example of a hypothetical industrial firm. The physical, processing, or manufacturing system shown at the bottom is controlled and managed by decisions that are worked out at various levels of hierarchy. The processes in this system are directly influenced by devices or rules which belong to the domain of control and shop-floor engineers. The engineers are given, from higher levels, short-

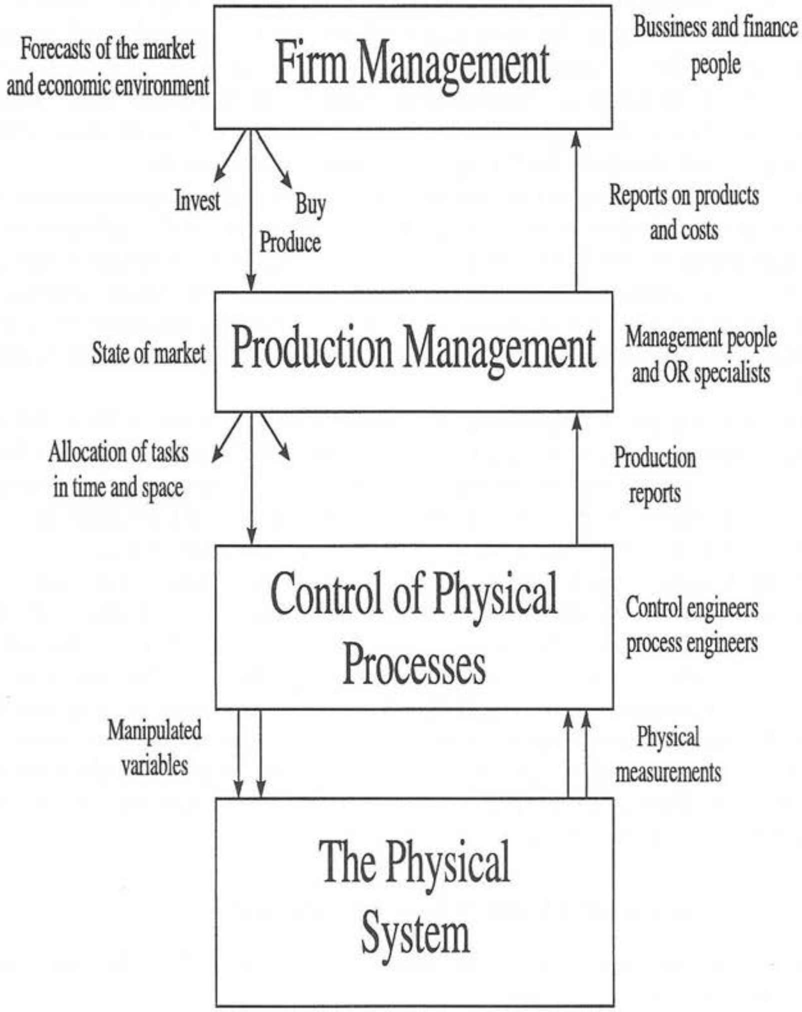

Figure 2. Differentiation of control and decision problems in a hierarchical structure (Findeisen, 1997).

term production assignments and their allocation in time and space. They respond by submitting production reports. Next is the domain of production management, where the overall "production" decision of the company executives will be subdivided into detailed instructions, with adequate attention paid to the cost. The information concerning both the production and cost, consolidated to the degree permitting the company level to operate efficiently, will constitute the response. The company management, shown at the top of Fig. 2, has much more to do with business, finance and market considerations than with the physical processes. Among other things, they decide what to produce, what to buy rather than produce, and in what to invest for the future.

The structure shown in Fig. 2 is not much more than a naive example. Nevertheless it may serve to convey to the reader how linguistically different may be the information exchanged between the levels or domains of a decision hierarchy, as well as how different the languages people speak within those domains will be. It would be a strong requirement, however, that the language of information exchanged between two neighbouring domains or levels be understandable to both.

One more feature of a hierarchical decision structure seems to be worth mentioning. The information about physical processes and phenomena in the system itself is less detailed, and the required information concerning the environment, including appropriate forecasts, becomes richer as we go up the hierarchy. Fig. 3 illustrates this feature, with some reference to the example of Fig. 2.

To finish these considerations, let us ponder the perception of a decision unit placed at a given level and location within the hierarchical structure. From its point of view, the "controlled system" is all that is placed below. The physical system, e.g., the process installations of an oil refinery or the airplanes of an airline, will be included, but so will the decision units belonging to all the levels below. If some of these decision units are goal-conscious, i.e., if they follow their own interests and refuse to act according to the pre-determined decision rules, then their freedom of behaviour must be reflected appropriately in the image and description of the system.

4. The design of hierarchical structures

Extending to some degree our considerations, let us underline the main characteristic features of a hierarchical structure:

- The units on the lower levels are in control of smaller parts of the system (differentiation of "the scope of authority"), they also usually operate with the perception of shorter time intervals.
- The decision unit at the top has the authority over the entire system and takes care of the full time interval of its operation.
- The degree of detail in the decisions and the frequency of intervention decrease as we go up the hierarchy. Simultanously, the decision problems become more complex and require more attention.

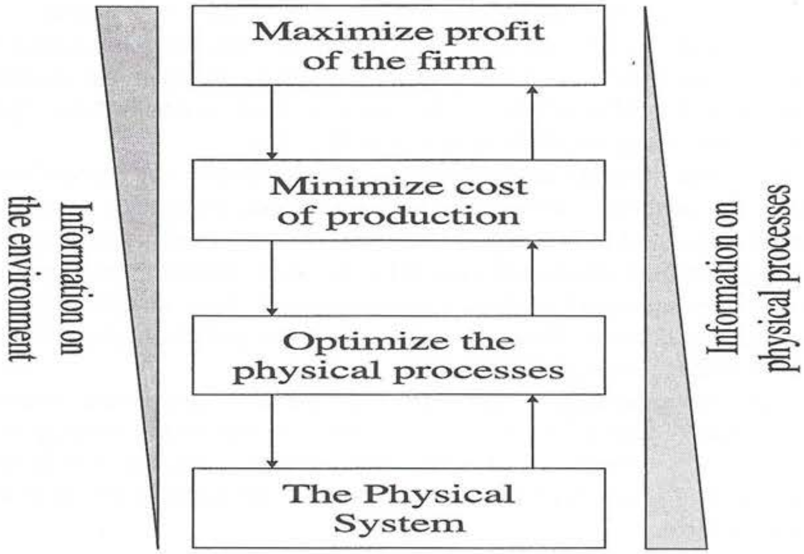

Figure 3. Differences in the scope of information on the system and its environment, required at various levels of control (Findeisen, 1997).

- The interests of parallel, i.e., located at the same level, decision units are usually in conflict. This conflict can be neutralized by the supreme unit, provided it has suitable coordination instruments at hand.
- A different scope of information about the system and its environment is available to decision units at various levels. There may exist a motivation to convey distored information to a higher level.

The design of a control or decision structure for a given system (Fig. 1) must begin with the setting of the fundamental attributes, namely:

- who, that is, which decision unit, makes a particular decision – "allocation of authority",
- what is the task to be fulfilled by a given decision unit (supressing the disturbances, minimizing the cost, etc.) – "allocation of tasks",
- on what the decisions will be based – "allocation of information",
- what kind of decision mechanism shall be used at various points of the structure (decision rules, optimization programs, decision support systems et al.).

Certainly, there is a lot of room for a large number of alternative designs that should be analyzed. There is no more effective tool for this purpose than a computer simulation which utilizes a model of the controlled system, a model of its environment and, last but not least, the models of the behaviour of the proposed decision units.

Contrary to the first impression, the use of a computer simulation is very labor-consuming. In any case of realistic complexity, one has to analyze a large number of alternatives. It takes a lot of know-how, intuition and experience to generate better alternatives on the basis of previous simulations. Special software is sometimes available to facilitate this effort.

At this point, it makes sense to indicate what is the role and place of control theory in the analysis and design of complex control structures. I am rather convinced that it is a role of importance. It is true that a problem of significant complexity, size and constraints cannot be completly solved. Nevertheless, the existing theory can supply reliable premises for the choice of instruments and methods of coordination, of ways to utilize information, of procedures for conflict situations, risk assessment and the like.

The following warning is therefore fully justified: performing simulation studies without being guided by a thorough knowledge of the existing theory may be not only excessively time-consuming, but also involves the danger of considering alternatives that are far from utilizing the available potential of the controlled system.

5. Conclusions

The development of control theory and technology, with reference to complex systems and leading to hierarchical structures, started – as mentioned at the beginning – about 40 years ago. There were two main streams of this development, intermixed in practice.

The first stream had its roots in mathematical programming, in the decomposition-coordination approach to solving large computational problems. Transforming these concepts into the control area required that several new aspects be taken into account, such as real-time operation, changes in the environment, the capability to use on-line feedback from the controlled system, and the conflicts between decision units.

The other stream was born from the reasoning of engineers, who very early on noticed that an optimal control of a process can be split into two tasks: the stabilization or path-following, rather continuous in nature, and an optimization of the desired trajectory, where the latter task is performed periodically. This idea gave rise to structures with varying frequency of intervention, as well as to structures with varying time horizon at the consecutive levels of a hierarchy – both of great practical importance and in full agreement with common sense.

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