

HUMAN FACTORS IN OPERATIONS DESIGN

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ABSTRACT

There are several underlying factors in the design of an operations organization to control a high technology spacecraft tracking system. The first is the principle of differentiation and integration. The multitude of tasks must be divided so that each individual or team can accomplish assignments without being overloaded. Then, the efforts of all the elements in the organization must be integrated for a consistent attack on the problem of tracking a spacecraft. The differentiation tends to be primarily along technical or functional lines, and by time span, but there are other considerations. The integration is provided by the organization's coordination and control elements.

Operating positions can be designed to be procedurally operated, knowledge operated, or somewhere in-between. "Procedurally operated" means that the operator follows a strict procedure. He does not need to know how the system works, only which procedure to follow. A "knowledge based" operating position means that the operator understands the system sufficiently well to know what to do to accomplish a task. He does not need written procedures. The selection of either procedural based or knowledge based operations influences the operator skill level required, the organization design, and the support required. The system's uncertainty level, stability level, and complexity are examined to evaluate the level of procedural operation possible.

INTRODUCTION

One of the key elements in the success of an organization is that its structure matches its needs. This applies to scientific as well as commercial organizations. When there is a mismatch between structure and the requirements of the environment in which the organization operates, efficiency is reduced. In extreme cases, the organization may not be able to continue in operation. Organizations seem to develop their structure in a chaotic and haphazard manner, but it is, in fact, not as chaotic as it seems. Organizations tend to develop their structure through a feedback process. A structure is tried, and if it is

successful, it is kept. If it is not successful, then it is discarded and something else is tried. Buckley (1) calls this the morphogenic property of organizations. An organization modifies its own structure to respond to its environmental needs. Lawrence and Lorsch (2) relate this to a cybernetic process through which an organization's members compare the desired results of a strategy with the actual results. When an acceptable performance is not obtained, the organization is adjusted, hopefully in the direction of improving performance.

This self adjusting process will usually produce an effective organization. However, it does have some potential problems. When the feedback sensitivity is insufficient, the organizational adjustment will not be made correctly and the organization's efficiency will most likely be degraded. An example is when the environment changes for an older organization that has operated the same way for years. The organization will often fail to detect this change, and not make the necessary adjustments. Often, organizations will understand that they have difficulties without knowing the cause of the difficulties. This may be due to the inexperience of the management or it may be due to the subtleties of the environment. It would be preferable to have some theoretical foundation on which to base the restructuring of the organization to meet new environmental needs. The following sections will present a theoretic foundation based on the principles of Differentiation/ Integration and Procedural/ Knowledge based operations.

DIFFERENTIATION/INTEGRATION

Lawrence and Lorsch (2) present the organizational design principle of Differentiation and Integration. This is a formal statement of the common wisdom that, in order to accomplish a big job, it must be divided up in some logical way. The separate efforts must be coordinated so that they work towards a common goal, i.e., they must be integrated. This principle provides a tool for analyzing organizational environments and organizational problems, and relating them to the organizational structure.

We will explore the differentiation/integration processes and relate them to the organizational structures presented in the previous DSN Operations organization papers in this session.

Differentiation

Five basic differentiation methods are used in analyzing the individual DSN Operations organizations. They are:

- Functional Differentiation
- Technical Differentiation
- Time Span Differentiation

Customer Differentiation

Product Differentiation

Functional differentiation is specialization by function performed. In a manufacturing organization, production is clearly a different function from engineering. Except for very small organizations, the two functions do not mix well and it is best to have the organization differentiated on that basis. The DSN Operations Organization (3) is differentiated along the functional items of Operations and Control Analysis, Scheduling, and Planning. These are separate functions and provide a natural differentiation.

Technical differentiation is specialization by areas of technology. For example, operations activities in the spacecraft telemetry and in the spacecraft command areas each require extensive training and experience for proficiency. It may be too much to expect that an individual or a team can be proficient in both. So, telemetry and command system operation provides a natural organizational differentiation.

Time span differentiation is based on the time over which a task is performed. The operations teams are confronted with tasks that require an almost immediate reaction. A task that lasts an hour is a long time. The planning activity has a long time span. A typical task, writing a planning document for example, requires weeks or months for completion. The overall planning task may last for several years. An individual's cognitive processes tend to adapt to the task time span. A short task is handled differently from a long task. It is very difficult for an individual or an organizational entity to work with short and long time span tasks at the same time. Typically, the long-time span task is given a lower priority by the individual and is not effectively pursued. Time span is a natural organizational differentiation.

Customer differentiation is specialization by customer, or in the case of the DSN Operations organization, the Flight Projects using the Network facilities. It is based on the observation that various customers tend to have different needs and different ways to approach their activities. Customer differentiation then is a natural organizational differentiation for those activities which are not standardized.

Product differentiation is based on the construction of different products or unit outputs. Often each product from an organization requires different inputs, a different setup, different skills and sometimes different management requirements. For example, the manufacturing of small control relays and large power relays would probably be on separate production lines because of the difference in production methods required.

The amount and type of differentiation required in an organization depends on the environment homogeneity. A very homogeneous environment requires minimal

differentiation and the type of differentiation may be quite arbitrary. In military organizations for example, there is very little natural differentiation in infantry units. The existing differentiation is based on the need to optimize the unit commander's span of control. On the other hand, a very complex technical or scientific environment would require deep differentiation along very specific lines. The DSN Operations Organization is an example of this environment, and the organization reflects this requirement for highly differentiated and specific organizational entities.

In complex environments it is common for more than one type of differentiation to apply to a organization's structure. For example, an organization may consist of basically technically differentiated units with time span differentiated subunits.

Integration. Integration is the process of controlling and coordinating the differentiated activities to produce a consistent effort towards a common goal. For homogeneous environments with minimal differentiation, the integration function is performed by line management. Again, the military infantry organization is a good example. For more complex environments with highly differentiated organizations, it becomes difficult for line management to accomplish the necessary integration. As Lawrence and Lorsch(2) point out in relation to conflict management as well as overall coordination, in order to be effective the power to influence must be where the knowledge exists. Successful highly differentiated organizations that require tight integration develop individual coordinators, cross-unit teams and sometimes organizational entities whose basic purpose in the overall organization is to achieve the necessary integration. Sometimes intergroup interfaces as well as interfaces with outside organizations are controlled by formal negotiated agreements.

DSN Organizational Analysis

It would be interesting to look at the DSN Operations Organization and analyze it in terms of the Differentiation/Integration Principle.

Operations Organization. The overall DSN Operations Organization (3) is differentiated into four functional units. The actual operation of the Network is performed by the Operations Group. The technical analysis of performance and failures is performed by the Analysis Group. The Network scheduling is performed by the Scheduling Group, and the Planning Group performs the planning function. There is also an element of time span differentiation in the DSN Operations Organization. The Operations and Analysis Groups operate with a relatively short time span. The Scheduling Group has a wide time span range and is further differentialized accordingly. The Planning Group operates with a long time span.

Because of the clear demarcation between the functional activities of the groups, integration requirements are small. Most operational interfaces are defined by formal agreements and procedures. Conflict resolution is first attempted by negotiation between elements of the functional units and if not successful, it is then resolved by line management.

Operations Group. The Operations Group (4) is responsible for the real-time operations and control of the network. It is a very short time span operation. There is a geographical differentiation in that there is an operations team at the Network Operations Control Center (NOCC) in Pasadena, Calif. and separate teams at each of the Deep Space Stations (DSSs). In addition, the NOCC Team is organized with a controller for each DSS. Because of the critical nature of the operations at the DSSs and the NOCC, very tight integration is required. This is achieved at the DSSs with a shift supervisor coordinating the activities of the DSS operations teams. At the NOCC, a Track Chief coordinates the activities of the station controllers, and provides an interface with other operations activities. An Operations Chief coordinates the customer project interface and the tracking activities with the Track Chief.

Analysis Group. The Analysis Group (5) is responsible for the analysis of the Network performance and for failure analysis. Again, the time span of their operations is relatively short. The group is differentiated in two ways, first by technology, then by time span. There are units for each of the major technologies used in spacecraft operations: telemetry, command, and tracking. Some attempts have been made to combine different technologies in a single operating position, but there is concern that the resulting demands on the operator for understanding both systems well will overload him and produce operator errors. Also, the technology oriented analysis teams are differentiated by time span. A real-time unit works on the immediate activities and problems. A nonreal-time unit works on the activities and problems which cannot be handled immediately and require more detailed analysis. The integration requirements for the analysis activity are minimal. They are resolved by formal procedures and by individual interaction and negotiation. Conflict resolution is accomplished by line management.

Scheduling Group. The Scheduling Group (6) manages the DSN resources to provide maximum spacecraft coverage for the customer projects. The products produced by this group are: the Long Range Schedule, the Middle Range Schedule, and the Short Range Schedule. This suggests a product differentiation with an element of time span differentiation. The group is organized with a unit team for each product.

The basic scheduling process has a linear flow, from the long range to the middle range to the short range schedule. Each schedule product uses the previous schedule as an input, and adds new information for more detail and for conflict resolution. The integration

requirements are small and are mostly based on preestablished procedures. Again, conflicts are negotiated by the team members with line management handling conflicts that cannot be resolved between the teams.

Planning Group. The Planning Group (7) provides the planning interface between DSN Operations and the customer projects. This implies a customer differentiation. A unit team is assigned to each Flight Project or Radio Astronomy activity. There is also an element of time span differentiation in the Planning Group organizational structure. The group has units providing long term planning and a unit that provides near term operations coordination. The long term and short term activities are best accomplished by separate teams.

Integration requirements between teams within the Planning Group are minimal. Any interaction is usually a conflict based on limited resources. These conflicts are resolved either by negotiation between teams or through priorities established by the budgeting agency.

PROCEDURAL/KNOWLEDGE BASE OPERATIONS DESIGN

One of the first considerations needed in the design of operations systems is whether the operations will be procedural based, knowledge based (8), or somewhere in-between. This issue is related to how the operators will operate the system. In a procedurally based operations design, the operator will run the system strictly by procedures. He doesn't need to understand how the system works, he only needs to know which procedure to apply. In a knowledge based operation design the operator knows how the system works and what he has to do to accomplish the task assigned. He does not need prior established procedures.

Procedurally Based Designs. Procedurally based operations designs are very attractive because they appear to be less costly. Lower skilled operators can be used. The lower costs may be illusory because of the increased costs of generating the necessary procedures. For successful procedurally based operations, the procedures have to be extensive and complete in detail. They have to cover every system condition both normal and abnormal. The generation of the procedures require a very high level staff which tends to increase the costs.

Three criteria must be considered before it is even possible to design a procedurally based operation. They are:

- Uncertainty
- Instability
- Complexity

Procedures cannot be written for system operation when the basic process being controlled by the system has a high level of uncertainty. Or another way of thinking about it, procedures cannot be generated when the requirements on the system are not known or cannot be predicted.

When the process being controlled by the system changes, that is it is unstable, the system itself must be changed to adapt to the new process characteristics. Therefore, the operational conditions, and specifically the procedures, will have to change. This usually increases the costs. And when the process is very unstable and the system changes rapidly, it may not be possible for the procedure changes to keep up with the system changes. Outdated or inadequate procedures create a high risk situation for procedurally based operations.

Systems that are highly complex require an excessive number of procedures for procedural operations. The cost for generating the procedures becomes excessive. Also, at some level of complexity, the interrelationships among the system elements become so involved that it is impossible for the procedure writer to understand them. At that point procedures can no longer be produced.

A prerequisite for procedural operation is that the operator must be able to determine the system state so that he can choose the correct procedure for subsequent activities. This places a requirement on the system designer to provide the visibility into the system state, which enhances the procedural operation.

Knowledge Based Designs. A knowledge based operations design avoids the problems associated with procedural based operations. In knowledge based operations, the operator understands the system sufficiently to make good use of his judgement in operating the system. The operator can accommodate uncertainty. When something unexpected occurs, he can determine the proper action from his own knowledge or his ability to gain the required knowledge from documentation or other persons. The knowledgeable operator can adapt to an unstable system environment.

In a complex system environment, the knowledge based operator has a significant advantage over the procedure writer in deciding what to do in a specific situation. The

knowledge based operator is using immediate information usually in a limited context, thereby reducing the complexity that he has to consider. The procedure writer writing a procedure to cover the same situation is working very much in advance of the actual situation and must use projected information. This is a more abstract and difficult process.

An adverse consequence of electing to use a knowledge based operational design is that higher skilled operators are required, and they are in general more costly. Also, the training required is more extensive and of a different nature than the training for procedural based operation. Whereas the training for procedural based operations should be oriented towards helping the operator relate system state and the correct procedure, the training for knowledge based operations should be oriented towards developing the operator's internal model of the system. The internal model is the concepts and relationships which the operator has in his mind that he feels represents the real system. It is how he sees the system. A good internal model is essential in knowledge based operations.

Procedural vs. Knowledge Based Operations. In designing an operations organization, the above three criteria must be considered. In addition, other issues should be examined. The characteristics of the operator population will influence whether a procedural or a knowledge based operation should be selected. We can consider operators along two different dimensions in relation to the kind of organization selected. Operators vary over a skill dimension and over a preference-for-structure dimension. Operators who are highly skilled would most likely dislike a highly procedural organization design. It would limit their opportunity to exercise their skill. A knowledge based operational design is appropriate to highly skilled operators and a procedurally based operational design is appropriate to lower skilled operators. A non-homogeneous operator population with mixed skill levels poses a problem for the operations designer. Regardless of the particular procedural/knowledge base dimension chosen, some of the operators are going to be mismatched with the system. One solution is to match the organization to the lowest level operator, and ignore the difficulties presented to the higher skilled operators. Another solution is to provide procedures for the lower skilled operators, and give the higher skilled operators the latitude to ignore the procedures and operate from their knowledge. If this course is taken, the system should be very carefully considered to avoid discrepancies which would inhibit either the procedural base or the knowledge based operation. This is particularly important in the design of the system display, as they may well be different for the two different kinds of operations.

The cognitive style of operators is another dimension to consider in terms of the appropriateness of either procedural or knowledge based design. Cognitive style is the habitual way people do things. The particular cognitive style model that is appropriate for this discussion is the Driver-Mock cognitive style model (9). One of the dimensions in this model is related to the individuals preference for either structured or unstructured

environments. Procedurally based operations design presents a very structured environment, and it would be reasonable to match this kind of system with operators preferring structuredness. On the other side, knowledge based operations designs are much less structured and would be appropriate to those operators preferring less structure. The determination of the prevailing cognitive style of an operator population can be made with questionnaire or interview survey techniques, or can be estimated from the background and experience of the operators.

Another important issue to consider is the criticalness of the operation. If the operation of a system is very critical, that is if the consequence of an error is large, then a procedurally based operations design is suggested. A procedurally based operations design provides for better control and consistency of operation than does a knowledge based design provided a procedural design can be implemented.

The choice of where on the procedural/knowledge based dimension the operations organization rests determines the kind of operators appropriate for the system or the kind of operators that should be hired. It influences the system design, particularly the design of the system displays. It also strongly influences the design of the support activities. Procedurally based operations design require more support because the information has to be fed into the system by generated procedures and instructions.

SUMMARY

The principles of Differentiation/Integration and Procedural/Knowledged based operations have been presented. They provide valuable tools for analyzing operations organization. Differentiation refers to the dividing of tasks by specializations. Integration refers to the coordination of these specialized units to achieve a common goal. Procedural based operations describes an operating mode in which the operators strictly use procedures and are not expected to understand how the system actually works. Knowledge based operations describes an operating mode where the operator uses his knowledge of the system to operate the system rather than rely on procedures. These principles provide tools for analyzing the operating environments in order to effectively match the organization.

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