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Publication date:
1982

Document Version
Publisher's PDF, also known as Version of record

RISØ-M-2341

THE USE OF FLOW MODELS FOR DESIGN OF PLANT OPERATING PROCEDURES

Morten Lind

Abstract. The report describe a systematic approach to the design of operating procedures or sequence automatics for process plant control. It is shown how flow models representing the topology of mass and energy flows on different levels of function provide plant information which is important for the considered design problem. The modelling methodology leads to the definition of three categories of control tasks. Two tasks relate to the regulation and control of changes of levels and flows of mass and energy in a system within a defined mode of operation. The third type relate to the control actions necessary for switching operations involved in changes of operating mode. These control tasks are identified for a given plant as part of the flow modelling activity. It is discussed

(continue on next page)

INIS Descriptors. AUTOMATION; CONSERVATION LAWS; CONTROL SYSTEMS; ENERGY BALANCE; FLOW MODELS; INDUSTRIAL PLANTS; MASS BALANCE; NUCLEAR POWER PLANTS; PLANNING; REACTOR OPERATION.

UDC 621.039.564

March 1982
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how the flow model deal with the problem of assigning control task precedence in time eg. during start-up or shut-down operations. The method may be a basis for providing automated procedure support to the operator in unforeseen situations or may be a tool for control design.

Presented at the IWG/NPPCI Specialists' Meeting on Procedures and Systems for Assisting an Operator During Normal and Anomalous Nuclear Power Plant Operation Situations, December 5-7, 1979, Garching, Federal Republic of Germany.

ISBN 87-550-0837-2
ISSN 0418-6435

Risø repro 1982

TABLE OF CONTENTS

INTRODUCTION

The succesful operation of process plant is dependent on a variety of procedures, for e.g. plant control, testing, maintenance, etc., here we will consider so-called operating procedures which are provided for plant control. We will especially be concerned with the plant information which is a sufficient basis for a systematic approach to the design of operating procedures.

In general, a procedure is a set of rules (an algorithm) which is used to control operator activity in a certain task. Thus, an operating procedure describes how actions on the plant (manipulation of control inputs) should be made if a certain system goal should be accomplished. The sequencing of actions, i.e. their ordering in time, depends on plant structure and properties, nature of the control task considered (goal) and operating constraints.

If described in relation to actual actions on the plant (start motor, close valve etc.) there is no formal difference between an operating procedure and the program which must be provided for an automatic sequential control system performing the same task. Thus, the present discussion is also relevant for the design of sequence automatics for plant control. In the following the term "operating procedure" will refer to both procedures used by the operator in plant control, and to programs for sequential automatics. Naturally, there will be some differences between operator procedures and programs for automatics for the same task. This is because there are differences in the specific nature of the "man-machine" and the controller-plant interfaces. However, these differences will not be considered here as they are not related to the problem of plant control on the level of description used here.

In the paper we will show how operating procedures can be structured into logically consistent parts by a decomposition into sequential and concurrent action sets. The decomposition is shown to originate from the topology of the pattern of material and energy flow in the plant, and to the nature of the specific control task considered. This analysis provides valuable information of how plant structure can be used explicitly in procedure design. It is shown how a category of models called flow models developed by the writer, can be used to represent flow topology in material and energy processing plants. Flow models will be used as a way of dealing with plant topology in procedure design.

The observation which leads to the consideration of flow models for procedure design is that e.g. start-up procedures for apparently dissimilar plant components as pumps and boilers show some common structural features. The reason for this is that the components are functionally equivalent in certain phases of their operation. Functional equivalence of components or systems can be expressed by using the language of flow models.

CONTROL TASKS IN PLANT OPERATION

In the operation of process plant we can distinguish between two categories of control which are related to different aspects of the coordination of plant functions. These categories are important for the discussion of task structure presented in the following section.

The first category includes the controls provided for optimization and for maintaining plant integrity during transients caused by external disturbances or by programmed changes in the operating conditions as e.g. changes of setpoints. Characteristic of this type of controls is that they are provided for a certain operating regime, i.e. they are not applicable if operating regime is changed. In material and energy processing plants, this category of controls performs a coordination of the redistribution of mass and energy stored in plant components.

The coordination problems discussed above are related to plant operations where structural changes do not occur. The second category of controls includes coordination problems related to changes in plant functional structure. This occurs when an integrated process must be established from a set of hitherto functionally unrelated plant components. In order to allow two process components to be connected, operational conditions for the two components must be equalized.(A boiler must be filled, heated and produce steam before it can be connected to the turbine. The turbine must be on correct speed before it can be synchronized with the grid etc.).

The division of a control task into subtasks according to the categories above leads to a decomposition of the associated goal and procedure into subgoals and subprocedures. Furthermore, to each task corresponds a plant subsystem which again is divided into subsubsystems by the task decomposition. However, plant subsystems obtained in this way will in general be overlapping, i.e. they will share components because the goal decomposition is based on the functional requirements and not on physical structure. In the following we will give a more detailed discussion of the decomposition of tasks and by this way give a meaning to the concept of task structure.

STATE-ACTION DIAGRAMS AND TASK STRUCTURE

According to the discussion in the previous section we can consider the operation of a process plant as a complex of activities related to several goal levels. The decomposition of a task into subtasks depends on what should be accomplished, i.e. the overall functional requirements, and on what can be accomplished within the constraints given by actual plant structure, choice of components, operational limits, etc.

We will now introduce the concept of a state-action diagram which can be used to represent the operational requirements to a process plant. This type of diagram is closely related to state-diagrams used in automata theory for the definition of sequential machines, i.e. systems which operate in discrete time and which can be in a discrete number of states. A simple example of a state-action diagram for power plant is shown in fig. 1. Here we have assumed that the plant can be in only two major states "No power" and "Full power". The states are indicated by circles and the arrows indicate possible transitions. To each arrow a set of actions in the system corresponds, specified in an operating procedure. A set of actions is indicated by a square box. It should be noted that if the actions are ignored (i.e. the square boxes are deleted), we obtain a state-diagram for the plant. Conversely, if the states are ignored, we get a representation of the action structure. This will also be denoted the procedure structure as every action set (square box) is prescribed in a procedure.

The concept of a state-action diagram introduced here is closely related to the so-called precedence networks used in project management for solving planning problems (see e.g. Burman, 1972). In addition to these formal similarities, there are, however, much deeper interrelations between the problems of procedure design for process plant and project planning problems. This will be discussed later in the present paper.

Thus the state-action diagram has two aspects when used for functional specification. It is a description of plant behaviour in terms of a set of states and the specified transitions between them, this information is contained in the state-diagram. Furthermore it is a specification to the plant environment of the relation between the individual control tasks involved in plant operation. In the state-action diagram a control task is defined by the structure shown in fig. 2.

It is seen that in relation to the task definition the initial plant state S_1 is a condition (the task is only initiated <u>if</u> the plant is in state S_1). Furthermore, the task goal is the final state S_2. (The goal is to transfer the plant to the state S_2). The way in which the transfer is made depends on the procedure used, i.e. on properties of the plant considered and design heuristics. This will be discussed later. As a state--action diagram can be divided into tasks as shown in fig. 3, it is a representation of the task structure.

It is clear that the specification of system function presented in a state-action diagram is related to a given level of detail in the description of the plant. Thus different choices of levels of detail lead to different state-action diagrams for the same system. Increasing the level of detail in the description leads to a modification of the diagram, because goals may decompose into subgoals (states for subsystems). This is illustrated in fig. 4 in a particularly simple case.

However, this decomposition cannot always be made because it is necessary to take into account the nature of the control tasks involved. This is the case for systems with strong internal variable interactions. Such systems must be considered as functional "wholes", and the control tasks associated with the change of state cannot even partially be related to a subsystem but is related to the behaviour of the whole. Fig. 5 illustrates this situation.

Now we have discussed the decomposition of tasks induced by division of the plant into subsystems, and it is realized that this decomposition may lead to concurrent subtask structures. In addition to this, we will consider task decomposition in the time domain and this will lead to subtask sequences. Assume that we have a control task relating system states S_1 and S_5 . If it is then possible to define a sequence S_2, S_3, S_4 of intermediate system states, we can decompose the task into a sequence of subtasks as shown in fig. 6.

The two decomposition principles described above can be used to break down a control task into a hierarchy of subtasks. As mentioned earlier, this decomposition cannot be done without taking system structure into consideration. A specification of a task describes what should be obtained. The decomposition into subtasks describes how the specifications are met within the constraints given by the physical structure of the plant.

FLOW MODELS

The function of process plant can be described in several ways depending on the modelling language used. Flow models as defined by the writer describe the topology of the pattern of material and energy flow in the plant. In this section we will give a short description of the basic concepts of flow modelling. For more details, see Lind (1979).

In flow modelling, the basic assumption is that every material and energy process can be described as an interaction between two fundamental types of processes. These are <u>storage</u> and <u>transport</u> processes. Storage processes include simple accumulation phenomena, i.e. pile-up of material or energy in a volume. But in addition to accumulation phenomena, storage processes may also include chemical processes, i.e. changes of material composition and changes of phase. Transport processes include the transfer of material and energy between two locations in space by convection, conduction and diffusion phenomena.

A processing plant is then described as an interconnection of material and energy storage and transport processes. The interconnection between processes is denoted a <u>boundary</u>.

The underlined concepts above constitute the basic vocabulary of flow modelling. The concepts are summarized in fig. 7, and we have furthermore introduced symbols used to represent the different processes in modelling. Using these symbols, a graph called the flow structure can be constructed from e.g. a plant flow sheet.

The major difference between the flow structure and a flow sheet is that a flow structure is a plant description in terms of fundamental processes whereas a flow sheet is structured according to processing components (unit operations). This implies that the flow structure contains information which is not explicit in a flow sheet. Furthermore, the fundamental nature of the flow modelling concept makes a flow structure a consistent category of models, i.e. rules for model modification can be given (see op cit). This is not the case for flow sheets.

In addition to the basic concepts defined above, the concept of a conditioned process and an aggregate is also used in flow modelling. A conditioned process is a process which can be influenced (controlled).

An aggregate is a collection of interrelated transport and storage processes. Aggregates are used for representing plant subsystems for which the internal structure is ignored. These concepts are summarized in fig. 8.

An example of a flow structure for a conventional power plant is shown in fig. 9. The flow structure describes plant functional structure in an intermediate operating regime during boiler start-up (boiler is filled with water and heating is initiated, steam produced is absorbed in the start-up system).

TYPES OF SYSTEM INTERACTION AND SYSTEM DECOMPOSITION

The description of a process plant by its flow structure makes a decomposition of the system into subsystems possible. The decomposition is in fact an integrated part of the modelling activity, as it is related to some basic decisions which should be made when formulating a system flow structure. The decomposition concerns the mode of interaction which two systems may have within the framework of flow models.

We have the following two basic types of interaction as illustrated in fig. 10.

Typical examples of interaction by conditioning are the influences on system operation from control systems or service systems which support main plant processes. Note that the conditioning subsystem may itself be a material and energy processing system. Interaction by exchange of material and energy covers the interconnection of the basic processes of storage and transport at a boundary and boundaries between more complex processing aggregates.

The major difference between the two types of interaction is that in the conditioning interaction a unique direction of control is given. (A change in operating conditions of A2 will not influence A1 whereas a change in A1 influences A2). In the case of interaction by exchange of material and energy, no unique direction of control can be given in general, as a change in operating conditions of either A3 or A4 may influence the other. The conditioning of A2 by A1 is a coordination of their functions, whereas the systems A3 and A4 are functionally integrated.

The functional integration can be broken by adding a conditioned transport process as shown in fig. 11. This modification implies that the functions of A3 and A4 can be coordinated.

Each plant system can now be decomposed into a main process system and its associated subsystems. The subsystems fall into two classes, conditioning and processing subsystems according to the basic types of interaction defined in fig. 10.

The main process includes processes which perform material and energy processes, the purpose of which is defined in relation to the system environment. Thus the main process may be a conditioning or a processing subsystem to another plant system.

The conditioning subsystems are different types of subsystems which either control the main process or establish and maintain proper function of the main system (lubricating systems, demineralizer and make-up systems, etc.).

Processing subsystems are subsystems which function as sources or sinks of material and/or energy in relation to the main system.

The decomposition is illustrated in fig. 12 where it is indicated that a main system may have several subsystems of the two types. The couplings of the main system to the environment are ignored in the figure.

Due to the recursive nature of the concept of system, a system can be decomposed into a hierarchy of subsystems as exemplified in fig. 13.

TASK DECOMPOSITION

If we now consider a given control task and the associated system, the decomposition of the system flow structure as described in the previous section will provide a division of the task into subtasks. This division depends on the nature of the task.

As discussed earlier, we have two categories of control tasks in process plant operation. The first includes changes of system state within the same operating regime, i.e. the system flow structure is unchanged. A change of state requires a coordination of the function of the conditioning subsystems for the system considered. This can be concluded from fig. 12 as the only way to change state of MS is to change the states of CS1, CS2 .... . The sequence of changes required can be deduced from the detailed structure of the main system flow structure and the change of state to be obtained in the different subsystems of the main system. As an illustration, let us consider the example in fig. 14. Here the main system has a tree structure internally.

If we now assume that the state of aggregate A1 should be unchanged, then the changes of state of C1, C2 and C3 (i.e. the control actions on the main system) should be coordinated to obtain this. This means that the conditioning of flows to A1 is an integrated task. If the state of A2 should be changed, then a control heuristic (or a suitable control system design method) must be chosen to determine the sequencing of the changes of state in C3, C4 and C5.

In a material and energy processing plant a proper heuristic would be to prevent transient pile-up of mass or energy in processing components (or aggregates). This heuristic which is related to plant safety would imply the following rule:

> If the material/energy content within an aggregate should be reduced/increased, then the source flows should be reduced/increased and/or sink flows should be increased/reduced. The choice depends on requirements to be met in neighbour aggregates.

We will not go further in the details of how a control task of the first category is decomposed into sub-tasks. This would require a discussion of the set of heuristics which can be used in connection with material and energy processing plants. This is a topic for further studies.

From the discussion above we can conclude that control tasks of type 1 are integrated, i.e. the state-action diagram defining the task has the structure as shown in fig. 5.

The second category of control tasks which coordinate changes in the operating regime of a system will now be discussed on the basis of decomposition of flow structure.

A change in operating regime includes a change of flow structure, i.e. either a functional interconnection of hitherto unrelated systems or a disconnection of a functionally integrated system. However, these operations require that the subsystems involved are properly conditioned, i.e. they must be in a state which allows an interconnection or disconnection to be done. This is necessary in order to avoid transient pehnomena which in the ultimate may cause component failures. This means that a control task of type 2 includes subtasks of type 1 (conditioning of subsystems before interconnection/disconnection).

Two systems which must be functionally integrated must have a potential for interconnection. This is usually provided by a conditioned transport node (representing e.g. a control valve). Thus we can base our discussion on the situation shown in fig. 15.

Here we have shown two systems decomposed into their subsystems (MS, CS and PS). The systems are interconnected by a conditioned transport node. Two states of the subsystem conditioning the transport process correspond to functional interconnection and disconnection (opened and closed valve). The subtasks related to the interconnection of MS1 and MS2 would then be (it is assumed that they are disconnected, i.e. it is a condition for the coordination task that CS1 is in proper state):

1) Conditioning of MS1, i.e. the state of CS1 must be changed.

2) Conditioning of MS2, i.e. the state of CS3 must be changed.

3) Coordination of MS1 and MS2. This includes the change of state of CS2.

It should be noted that all subtasks are of category 1. The state-action diagram corresponding to this interconnection task is shown in fig. 16. An analysis in the case of system disconnection will lead to a similar state-action diagram.

As before we will need heuristics to determine the sequence of subtasks. As an example we could mention the following heuristic

> Material flow boundaries must be established before pure energetic boundaries. This heuristic prevent that extreme energy densities occur in aggregates (i.e. high pressures or temperatures).

But as before, a more detailed study is necessary to formulate a sufficient set of heuristics for material and energy processing plants.

As an example of a state-action diagram for a complex task fig. 17 is included. It shows the interrelations between subtasks in the first phases in the startup of a conventional boiler. The startup procedure is taken from Pedersen (1974) and described here into the format of a state-action diagram. In this example we can identify sequences of subtasks of the different categories discussed earlier. Furthermore, some of the underlying heuristics can be identified (e.g. fill the boiler drum with water and establish air/gas flow before starting the burners).

PROCEDURE DESIGN

The previous discussion have described how a control task can be decomposed into subtasks. It has been shown how the flow structure of the system and the nature of the control task determine the decomposition. Furthermore, it has been discussed how design heuristics can be used to determine the sequencing of the individual subtasks. In this way we have formulated a structured approach to procedure design. However the method do only consider the aspects of procedure structure which are related to plant topology. We have not considered the aspect of time and resources of material and energy. This bring us back to the discussion of the interrelations between procedure design and project planning problems.

The problem of project planning is usually separated into three phases(see e.g. Burman, 1972)

Planning: The planning phase include the analysis of the logic of the situation (interrelations between the individual jobs to be done) by arranging the jobs in an order of precedence. This correpond exactly to the decomposition of a control task into subtasks as described in the present paper. The result of the ordering of jobs is presented in a precedence diagram. Here we obtain a state-action diagram. These two diagrams are formally equivalent.

Scheduling: The scheduling phase include a conversion of the plan into a feasible schedule. This is obtained by analysing the plan (the precedence or the state-action diagram) with reference to the use of available resources i.e. time and material and energy supplies. This is one of the aspects of procedure design which is not covered in this paper. This means that scheduling is dependent on plant information as time constants of plant processes and of storage capacities. This plant information is not represented in the flow structure.

Supervision: The supervision phase include the monitoring and correction activities which must be made in order to ensure adherence to schedule (i.e. the planned operation). These aspects of operating procedures are discussed in Goodstein (1979).

OPERATOR SUPPORT

The method for procedure design presented above may be used as a basis for computerized on-line procedure construction. The operator could use the plant computer to generate procedures in situations which are not predicted by the designer.

Such a facility would be an integrated part of a system for computer assisted plant diagnosis.

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Pedersen, O.M.: An analysis of operator's information and display requirements during power plant boiler start. Risø-M-1738, Dec. 1974.

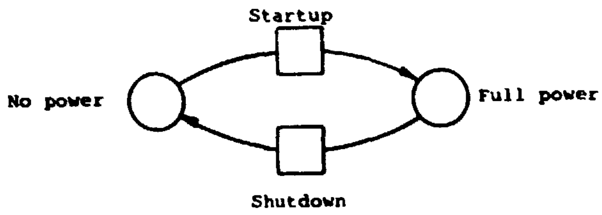


Fig 1. Simple state-action diagram.

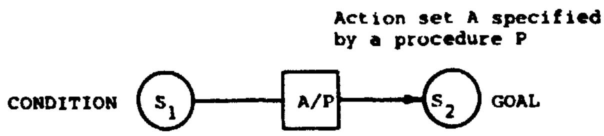


Fig. 2. A control task

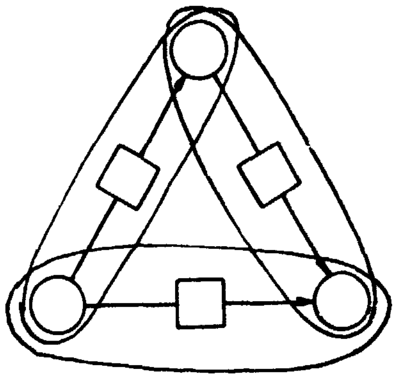


Fig. 3. Subdivision of state-action diagram into tasks

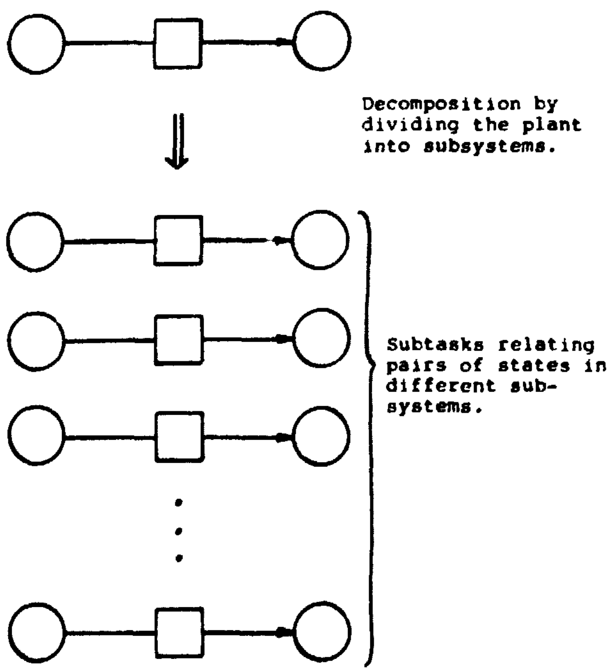


Fig. 4. Decomposition of a task into independent subtasks.

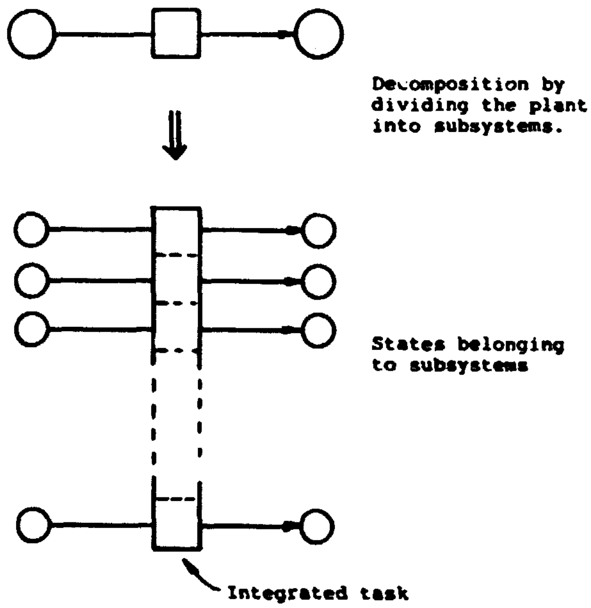


Fig. 5. Incomplete task decomposition when a functional whole is decomposed into subsystems

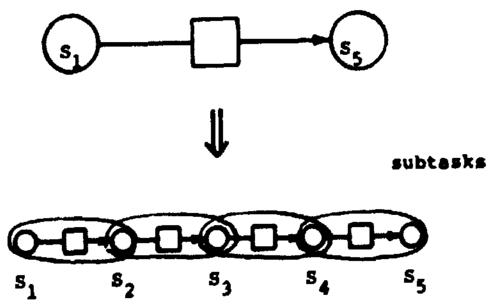


Fig. 6. Temporal task decomposition

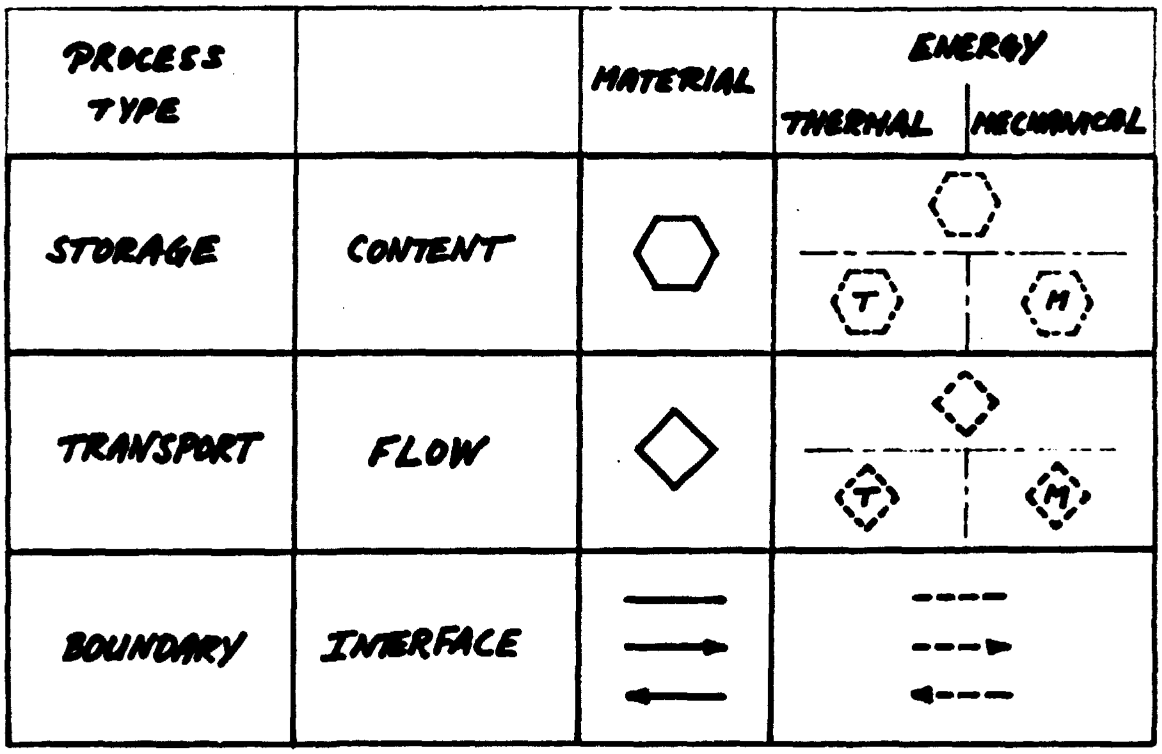


Fig. 7. Flow modelling concepts and symbols.

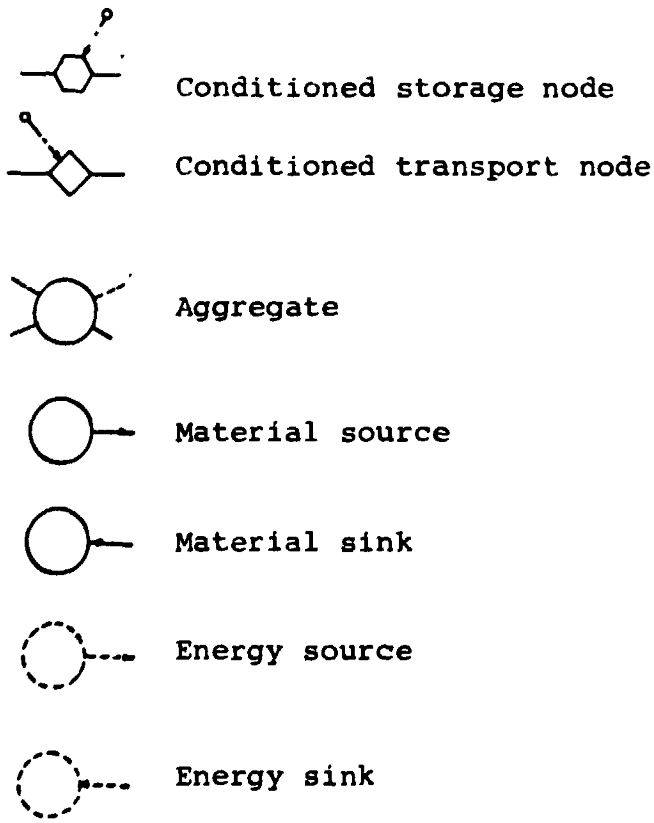


Fig. 8. Additional definitions

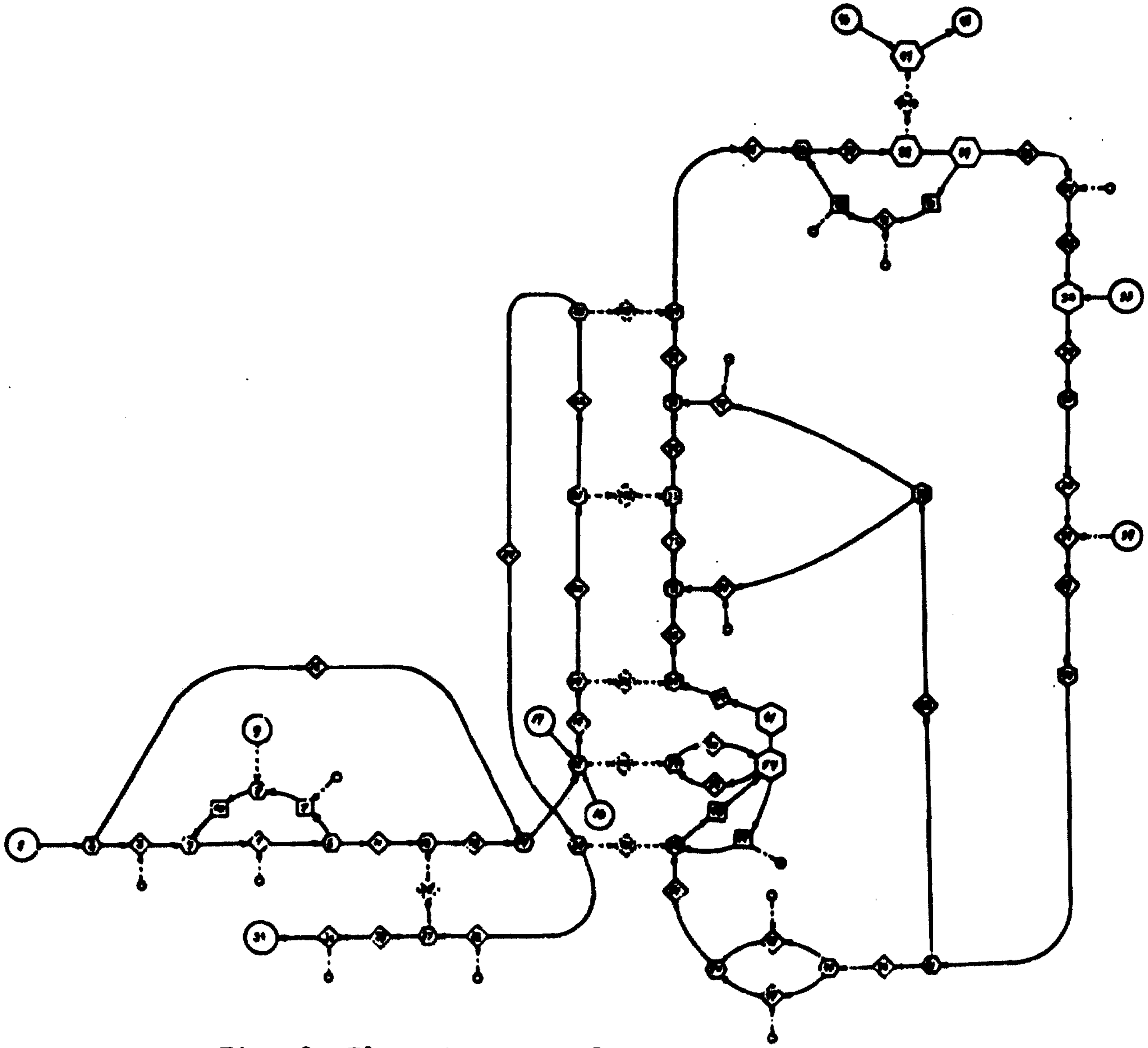


Fig. 9. Flow structure for a conventional power plant.

Fig. 10 Types of process interaction

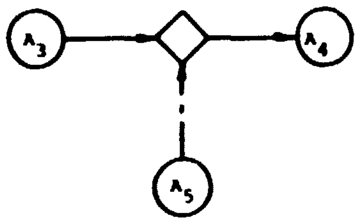


Fig. 11.

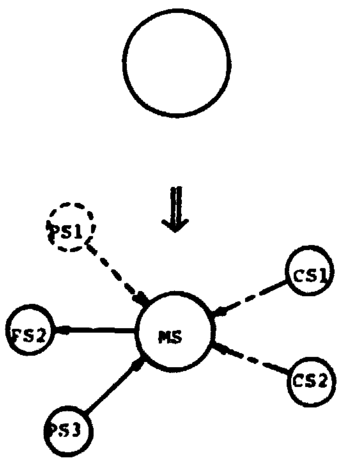


Fig. 12. Decomposition of system into main system and associated subsystems.

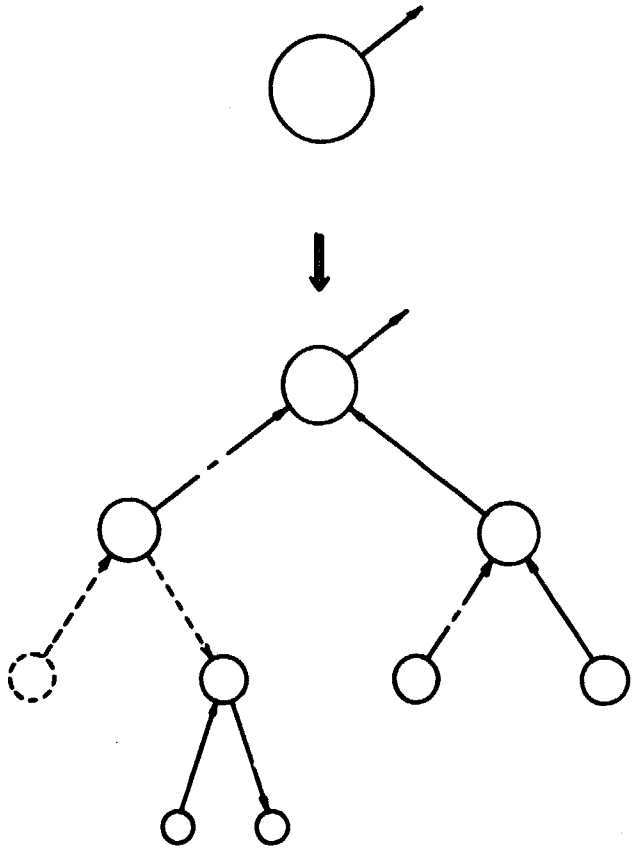


Fig. 13 Decomposition hierarchy.

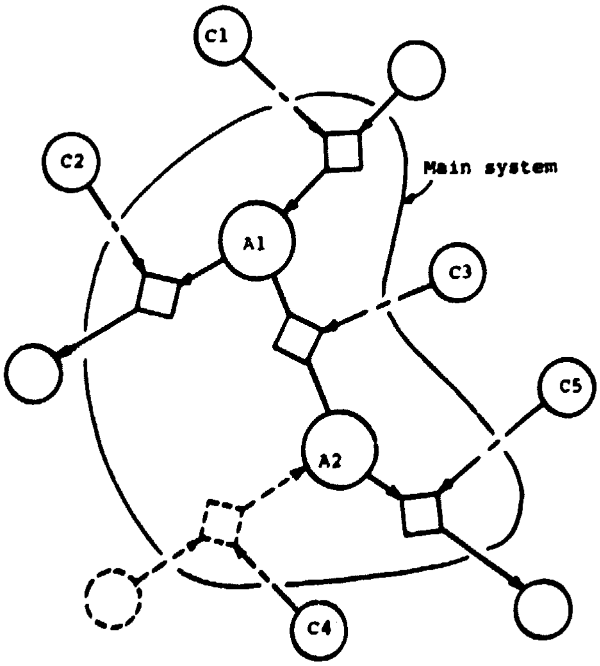


Fig. 14. Main system example.

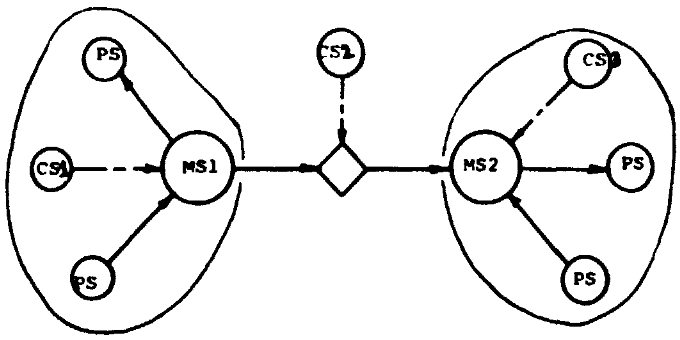


Fig. 15. Two interconnected systems

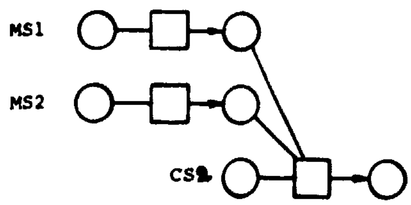
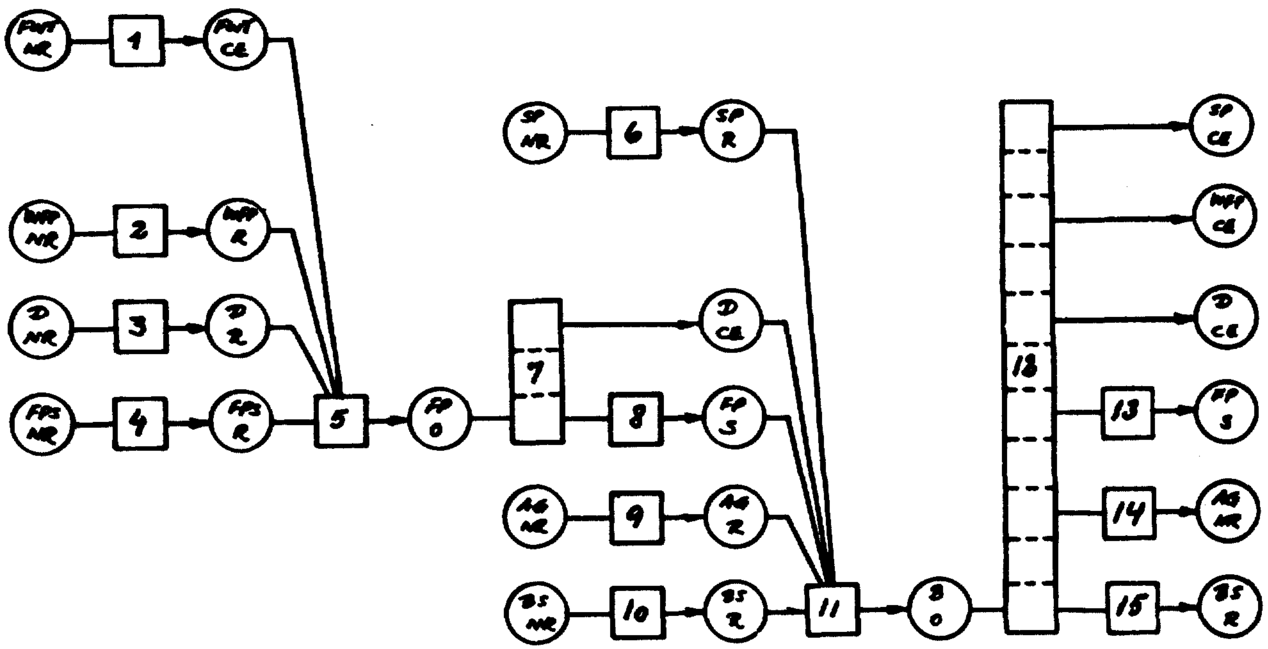


Fig. 16. State-action diagram for the inter-
connection of MS1 and MS2 in fig. 15.



SYMBOLS:

COMPONENTS OR SUBSYSTEMS

AG	Air/gas path
B	Burner
BS	Burner system (B and subsystems)
D	Drum
FP	Feed pump
FPS	Feedpump system (FP and subsystems)
FWT	Feed water tank
SP	Steam flow paths
WFP	Water flow paths

STATES

CE	Content established
NR	Not ready
O	Operating
R	Ready
S	Stopped

X ← Component or subsystem
S ← State

Control Task

Fig. 17. State-action diagram for boiler startup.

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Date March 1982

Department or group

Electronics

Group's own registration number(s)

R-6-82

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Abstract

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