6 Analyzing the Required Actions Prescribed in Emergency Tasks

As stated at the end of Chap. 4, the complexity of proceduralized tasks should be quantifiable by the concept of graph entropies if we construct a series of graphs representing the features of five kinds of complexity factors. In some respect, this requirement seems to be easily fulfilled because, for example, an ACG is directly comparable to the control flow graph of software. This implies that the effects of two kinds of complexity factors on the complexity of proceduralized tasks might be quantified from the ACG. That is, the first-order entropy of the ACG represents the contribution of logical entanglement on the complexity of proceduralized tasks, while the second-order entropy represents the contribution from the number of actions to be conducted by qualified operators. Unfortunately, we still need three more graphs that are able to characterize the remaining complexity factors: (1) the amount of information to be processed by qualified operators, (2) the amount of domain knowledge, and (3) the level of engineering decision.

Consequently, it may be necessary to meticulously analyze the contents of an action because the core of proceduralized tasks is to specify what should be done and how to do it. In other words, it is strongly expected that we can extract the necessary information to construct the corresponding graphs by scrutinizing the contents of an action. To clarify this aspect, let us look at the following explanations excerpted from Dougherty (1992).

> Potential rules in procedures, which we have generously assumed are candidates for rule-based behavior, include …
>
> 3. The symptom 'reactor level' in a BWR or 'subcooling margin' in a PWR.
> 4. The symptom 'Emergency Depressurization is Anticipated' in a BWR procedure.
>
> …
>
> The third case indicates that so-called symptoms may be simple instrumented parameters or more abstract or complex comparisons or interpretations. The fourth case is hard to analyze since the operant word is a human ability, anticipation, that may be used in variable, idiosyncratic ways by different people. Hence, it is hard to count the fourth item as an instruction at all (p. 254).

In other words, Dougherty criticizes the absence of essential contents of action descriptions, which results in the adoption of *variable and idiosyncratic ways* to accomplish proceduralized tasks (i.e., nonstandardized behaviors). Here, a departure from standardized behaviors implies the loss of an important benefit justifying why we have to use a procedure. Therefore, a systematic framework, by which the critical contents of an action are properly distinguished, should be determined first.

6.1 Key Contents of an Action Description

Existing works in the literature have stressed that there is a certain rule to write an effective action statement that directs what is needed to be done. For example, the Department of Energy (1998) made the following recommendation: "Complete the basic action step with supportive information about the action verb and the direct object. Supportive information includes further description of the object and the recipient of the object. Acceptance criteria, referencing, and branching are other types of supportive information … (p. 37)."

In addition, the Department of Defense (1999) explained that "The task inventory is composed of task statements, each of which consists of (a) an action verb that identifies what is to be accomplished in the task, (b) an object that identifies what is to be acted upon in the task, and (c) qualifying phrases needed to distinguish the task from related or similar tasks (p. 226)."

These recommendations give us an important clue to understand the key contents of an action description. That is, it is supposed that each action description can be decomposed into three parts: an *ACTION VERB*, an *OBJECT*, and an action specification. Since the meaning of *OBJECT* is self-explanatory (e.g., *a tangible and visible entity that is to be acted on*), it is worth focusing on the remaining parts.

6.1.1 Action Verb

Webster's New Millennium Dictionary of English defines an *ACTION VERB* as *a word belonging to the part of speech that is the center of the predicate and which describes an act or activity* (Webster 2008). In a technical term, the following definition seems to be more appropriate context: "A word that conveys action/behaviors and reflects the type of performance that is to occur (i.e., place, cut, drive, open, hold). Action verbs reflect behaviors that are measurable, observable, verifiable and reliable (Glossary 2008)."

This definition reflects the fact that an *ACTION VERB* is probably the most important part of describing an action. Subsequently, articulating *ACTION VERB*s should be the approach to characterizing actions to be performed by qualified operators. Table 6.1 summarizes the list of *ACTION VERB*s that has been commonly used in the EOPs of NPPs (DOE 1998; Jung 2001).

Table 6.1 Selected *ACTION VERB*s frequently appearing in EOPs

ID	ACTION VERB	Meaning
1	Align	Arrange equipment in a specific configuration to permit a specific operation
2	Close	Manipulate a device to allow the flow of electricity or to prevent the flow of fluids, other materials, or light
3	Cool (down)	Lower the temperature of equipment or environment
4	Depressurize	Release gas or fluid pressure
5	Determine	Find out; ascertain
6	Energize	Provide equipment with electrical power
7	Ensure	Confirm that an activity or condition has occurred in conformation with specific requirements
8	Increase	Produce a larger value
9	Isolate	Shut off or remove from service
10	Maintain	Hold or keep in any particular state or condition, especially in a state of efficiency or validity
11	Open	Manipulate a device to prevent the flow of electricity or to allow the flow of fluids, other materials, or light
12	Operate	Cause equipment or system to perform designated functions
13	Perform	Carry out specified actions
14	Reduce	Decrease a variable to meet a procedure requirement
15	Reset	Restore a piece of equipment, part, or component to a previous condition, parameter value, instrument set point, or mechanical position
16	Stabilize	Become stable, firm, steady
17	Start	Initiate the function of an electrical or mechanical device
18	Stop	Halt movement or progress; hold back
19	Throttle	Adjust a valve to an intermediate position to obtain a desired parameter value
20	Verify	Confirm, substantiate, and assure that a specific activity has occurred or that a stated condition exists

6.1.2 Action Specification

The next part is an action specification that might be *supportive information* that helps qualified operators to carry out an action or *qualifying phrases* needed to distinguish each action from related and/or similar actions. For example, let us recall the following two actions pertaining to making a smooth cookie batter, which are exemplified in Sect. 1.3.

A1 Cream together the butter and the brown sugar until smooth
A3 Using a mixer fitted with paddle attachment, cream butter and sugar

together until very light, about 5 min

Here, we can decompose the key contents of these actions into three parts as shown in Table 6.2.

Table 6.2 Comparing key contents of two arbitrary actions

Action description	Contents	Corresponding description
Cream together the butter and the brown sugar until smooth	ACTION VERB	Cream
	OBJECT	Batter (mixture of butter and sugar)
	Action specification	Until smooth
Using a mixer fitted with paddle attachment, cream butter and sugar together until very light, about 5 min	ACTION VERB	Cream
	OBJECT	Batter
	Action specification	● Until very light ● A mixer with a paddle (a dedicated means) ● Operation time (5 min)

From Table 6.2, it is evident that two actions share the same *ACTION VERB* as well as *OBJECT*. However, although action A3 is lengthier, it is expected that this action will be accomplished more easily than action A1. One plausible reason is the difference in the action specification. That is, the action specification of the former is quite subjective (i.e., until smooth) while that of the latter is objective (i.e., specifying how long the mixer is to be used). As a consequence, it is anticipated that the former action will require more cognitive resources to decide whether the batter is smooth or not.

In fact, Bovair and Kieras (1996) cited the result of a previous study pertaining to writing an effective procedural instruction:

> They found that the good and bad instructions could not be distinguished by text characteristics likely to affect reading comprehension such as length of text or length of sentences; in deed, some of the best instructions had the most complex syntax and sentence structure. The important differences between good and bad instructions seemed to be those of contents; in particular, poor instructions omitted important details like the orientation of parts in the assembly task, and often included the wrong level of detail (p. 222).

This result strongly indicates that even if the length of an action description becomes longer, it is much more important for qualified operators to provide appropriate action specifications. Conversely, if qualified operators feel any burden in performing an action, it is assumed that this burden would have been largely caused by insufficient action specifications. This means that analyzing the characteristics of action specifications will give an important clue in identifying the contents that should be included in an action.

6.2 Characterizing an Action

In order to identify the characteristics of action specifications, detailed analysis has been carried out for all the EOPs of KSNPs (Park *et al*. 2005). As a result, three radical elements related to action specifications and two types of peculiarities have been distinguished as summarized in Table 6.3.

Table 6.3 Characterizing scheme of actions included in EOPs

Category	Element	Predefined property
Action specification	MEANS	Designated means (DEG)
		Inherent means (INH)
		No means (NM)
		Local operation (LO)
	ACCEPTANCE CRITERION	Objective criterion (OBJ)
		Reference information (RI)
		Subjective criterion (SUB)
		No criterion (NC)
	CONSTRAINT	Objective constraint (OBJ_C)
		Subjective constraint (SUB_C)
		Reference information (RI_C)
		No limitation (NL)
Peculiarity	Selection (SEL)	Yes or No
	Continuous control (CC)	Yes or No

6.2.1 Means

A *MEANS* indicates an explicit method that specifies how to achieve the expected state of a given action. The *MEANS has four properties*: (1) designated means (*DEG*), (2) inherent means (*INH*), (3) no means (*NM*), and (4) local operation (*LO*). For example, let us compare the following three actions:

- Cool down the temperature of the RCS to 275°C using valve A
- Close valve A
- Cool down the temperature of the RCS to 270°C

It is evident that the goal of the first action is to cool down (*ACTION VERB*) the temperature of the RCS (*OBJECT*). To accomplish this goal, this action forces qualified operators to use the value A. In other words, even though other valves are available to reduce the temperature of the RCS, this action must be accomplished by manipulating the valve A. Therefore, *DEG* is assigned to the first action.

Meanwhile, the second action did not specify any method to close the valve A. However, the omission of a specific method seems to be acceptable, if it is assumed that the only way to close the valve A (i.e., the goal of this action) is to use the associated controller (i.e., the controller of the valve A). In other words, although there is no specification about *MEANS*, it is assumed that the action already implies the proper method if there is no choice for accomplishing its goal. Accordingly, in order to distinguish the term of *DEG*, the second action is regarded as an action that contains *INH*.

Similarly, the third action does not prescribe any specific method to lower the temperature of the RCS. However, the implication of this omission is completely different from that of the second action, because it is assumed that there are several equivalent methods to reduce the temperature of the RCS. This indicates that *NM* should be assigned to the third action, because qualified operators have to come up with an appropriate method to lower the temperature of the RCS.

It is to be noted that *NM* should be assigned to an action that does not manifest the associated components or equipment requiring the intervention of qualified operators. For instance, *NM* should be assigned to the action *align all the valves to transfer a coolant from Tank A to Tank B* because it does not specify the associated valves that are necessary to make a flow line from *Tank A* to *Tank B*.

As for the last, it is necessary to clarify the meaning of *LO*. Let us assume an arbitrary action, such as *ensure that a field operator stopped pump C*. In this case, it is obvious that the purpose of this action is to verify whether a field operator who is working in a local place successfully stopped the *pump C* or not. In this case, it would be difficult to determine which controller will be used, because the field operator is liable to select the most appropriate one available in that particular location. Therefore, in order to distinguish *NM* as well as *INH*, *LO* should be assigned to an action requiring the assistance or cooperation of field operators working at that location.

6.2.2 Acceptance Criterion

It is apparent that there are many actions requiring the decision of qualified operators, such as *verify SIAS is automatically actuated*. Accordingly, an *ACCEPTANCE CRITERION*, by which qualified operators confirm whether the goal of a given action is achieved or not, should be regarded as the important element of action specifications (DOE 1998).

In many cases, the *ACCEPTANCE CRITERION* articulates either the state that an *OBJECT* is expected to reach or any condition by which the current status of an *OBJECT* can be confirmed. Thus, we can consider four kinds of properties in characterizing the *ACCEPTANCE CRITERION*: (1) objective criterion (*OBJ*), (2) reference information (*RI*), (3) subjective criterion (*SUB*), and (4) no criterion (*NC*).

First, let us recall *close valve A* action whose expected status is a fully closed valve position. Therefore, the success or failure of this action can be easily determined by checking a valve status indicator. Similarly, in the case of *verify pressurizer pressure is less than 123.9 kg/cm²* action, qualified operators can confirm whether the current status has reached the expected status or not because there is a clear *ACCEPTANCE CRITERION* – less than 123.9 kg/cm^2. Therefore, any *ACCEPTANCE CRITERION* that provides an unbiased yardstick is regarded as *OBJ*. Table 6.4 summarizes typical examples of *OBJ*.

Table 6.4 Several examples of *OBJ*

Property	Example	The associated action
Dichotomous	Open/Close	Close main feed water isolation valves (MFIVs)
	On/Off	Verify safety injection actuation signal (SIAS) is actuated
	Start/Stop	Stop all RCPs
Discrete value	≥ (greater than)	Verify subcooling margin is greater than 15°C
	≤ (less than)	Verify pressurizer pressure is less than 123.9 kg/cm^2
Explicit range	135~165 kg/cm^2	Verify pressurizer pressure is maintained within 135~165 kg/cm^2
Trend	Increase	Verify pressurizer pressure is increasing
	Decrease	Verify pressurizer pressure is decreasing

Second, although the *ACCEPTANCE CRITERION* is manifested in the required action, there are times when qualified operators are not able to directly apply it. For example, let us consider an action, such as *verify sufficient safety injection (SI) flow is delivered to RCS (refer to SI delivery curve)*, whose goal is to confirm the delivery of a *sufficient* SI flow. Here, should to be noted that the satisfaction of the expected state should be determined by a reference curve like Fig. 6.1.

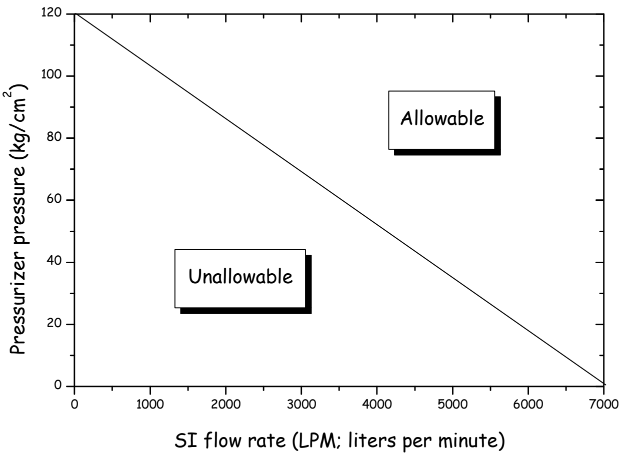


Fig. 6.1 Hypothetical curve to determine the delivery of a sufficient SI flow

In Fig. 6.1, in order to confirm the delivery of a sufficient SI flow (i.e., *acceptable* area), qualified operators have to compare the current SI flow rate with the expected rate that varies with respect to pressurizer pressure. This implies that qualified operators need to confirm the satisfaction of an *ACCEPTANCE CRITERION*, not by the simple observation of an associated indicator but by the integration of additional information to identify the status of an ongoing situation. For this reason, *RI* is considered one of the properties of the *ACCEPTANCE CRITERION*. Table 6.5 shows several actions whose acceptance criterion can be confirmed by *RI*.

Table 6.5 Properties of *RI* with the associated actions

Property	Meaning	Associated action
Time	Reference information is given by a certain period of time	Verify feed flow has been supplied for the preceding 5 min
Figure/Chart	Reference information is given by figures or charts	Verify sufficient SI flow is delivered to RCS (refer to SI delivery curve)
Table/List	Reference information is given by tables or lists	Cool down the temperature of the ruptured SG to a target temperature (refer to *Table X*)
Equation/Formula	Reference information can be obtained from equations or formulas	Determine the leak rate of an isolation valve (refer to *Equation Y*)
Static configuration	The information about component configurations is used as reference information	Close isolation valve linked to the discharge line (i.e., a valve linked to the discharge line can be determined by static configuration)
Dynamic configuration	Component configurations that vary due to an ongoing situation are regarded as reference information	Isolate auxiliary feed water flow delivered to the ruptured SG (i.e., the ruptured SG dynamically varies with respect to the location of ruptured tubes)

Third, there are times when qualified operators suffer from an ambiguous *ACCEPTANCE CRITERION*. For example, let us consider *verify pressurizer pressure is abnormally decreasing* action. Unfortunately, qualified operators will likely make different decisions when they are faced with this action. This is probably because the subjectivity (or ambiguity) of the *ACCEPTANCE CRITERION*, which forces qualified operators to make a tricky decision – *which tendency represents abnormally decreasing pressurizer pressure*? or *how can we confirm the decrease of pressurizer pressure is not a natural phenomenon in this situation*? Accordingly, an *ACCEPTANCE CRITERION* that is able to provide a biased yardstick is referred to as *SUB*. Table 6.6 shows typical examples.

However, the worst case is an action that does not have any *ACCEPTANCE CRITERION*. In this case, as with the last property, *NC* is assigned to the action. For example, *NC* should be assigned to *stabilize pressurizer pressure using pres-*

surizer spray valves action because this action consists of *ACTION VERB* (stabilize), *OBJECT* (pressurizer pressure), and *MEANS* (pressurizer spray valves) without any specification about the *ACCEPTANCE CRITERION* (i.e., how to define the status of a *stabilized* pressure).

Table 6.6 Typical examples of *SUB*

Property	Example	Associated action
Status	Uncontrollable (or controllable)	Verify there is no SG whose pressure is decreasing in an uncontrolled manner
	Abnormal (or normal)	Verify pressurizer pressure is abnormally decreasing
	Unstable (or stable)	Ensure the pressure of each SG is stable
Potentiality	The possibility of restoration	Determine that at least one AC (alternating current) emergency bus can be restored
	Necessity (or anticipation)	Open supply breakers for all unnecessary DC (direct current) loads

6.2.3 Constraint

A *CONSTRAINT* represents a restriction (or limitation) that has to be obeyed to accomplish the goal of a given action. At a glance, the purpose of the *CONSTRAINT* seems to be similar to that of an *ACCEPTANCE CRITERION*, because they commonly deal with a condition to be satisfied. This implies that the identical set of properties considered in the *ACCEPTANCE CRITERION* can be applied to the *CONSTRAINT*. That is, the *CONSTRAINT* has four kinds of properties: (1) objective constraint (*OBJ_C*), (2) reference information (*RI_C*), (3) subjective constraint (*SUB_C*), and (4) no limitation (*NL*).

However, it should be noted that there is a difference between the *ACCEPTANCE CRITERION* and the *CONSTRAINT* because the former specifies the expected (or final) status of an *OBJECT* while the latter clarifies a condition related to an *ACTION VERB* or a *MEANS*. For example, let us consider *open steam bypass control system (SBCS) valve #1 to 100%, until RCS temperature is less than 260^{o}C* action. In this action, the *ACTION VERB*, *OBJECT*, and *ACCEPTANCE CRITERION* are o*pen*, *SBCS valve #1*, and *100%*, respectively. However, the phrase starting with *until* denotes an additional condition that fixes when qualified operators have to close SBCS valve #1 (i.e., OBJ_C). Similarly, the *CONSTRAINT* of *close feed water control valve #1 when SG level becomes stable* action is *SUB_C* because it subjectively defines the timing for when qualified operators have to close feed water control valve #1 (e.g., the interpretation of a *stable* SG level would be subjective).

6.2.4 Peculiarity

In characterizing an action, the aforementioned elements are identified from the point of view of action specifications. In addition to this, it is indispensable to consider a *peculiarity* that pertains to the performance of an action. It is to be noted that, although there would be more peculiarities, two types of peculiarities are considered in this book. The first one is related to the selection of an action. Let us look at the following procedural step containing equally acceptable actions.

> **IF** necessary, perform **ANY** of the following.
> - Stop HPSI (high pressure safety injection) pumps
> - Throttle HPSI flow
> - Operate PLCS (pressurizer level control system)
> - Operate charging pumps

From the point of view of action specifications, Table 6.7 shows the result of decompositions of the first two actions.

Table 6.7 Action descriptions, elements, and their properties with respect to equally acceptable actions

Action description	Element	Property
If necessary, perform any of the following	OBJECT	Any of the following
	MEANS	NM
	ACCEPTANCE CRITERION	SUB (necessity)
	CONSTRAINT	NL
Stop HPSI pumps	OBJECT	HPSI pumps
	MEANS	INH
	ACCEPTANCE CRITERION	OBJ (dichotomous)
	CONSTRAINT	NL

In Table 6.7, it is observed that there is a problem in characterizing the first action. That is, from the point of view of action specifications, the first action seems to be very unusual because its *OBJECT* does not clarify a tangible and visible entity, such as HPSI pumps. Meanwhile, this action forces qualified operators to select an appropriate *OBJECT* (i.e., any action must be done). Therefore, to resolve this problem, it would be better to define another property by which the nature of the selection can be represented. As a result, instead of considering five actions, the above procedural step is regarded as a procedural step that consists of four actions with the *peculiarity* of *SEL* (Table 6.8).

Another *peculiarity* is related to an action that requires the continuous control activity of qualified operators. A typical example is an action that forces qualified operators to adjust a process parameter, such as *cool down the temperature of RCS* *to 275°C using valve A*. To accomplish this action, qualified operators should continuously adjust the open position of the associated valve as well as monitor the RCS temperature until the target temperature is reached. Therefore, this action seems to be very unique, because it impels qualified operators to continuously use their cognitive resources for an extended period. For this reason, it is necessary to distinguish actions requiring a continuous control activity from other actions by assigning them the designation *CC*.

Table 6.8 A set of actions that are interlinked by SEL property

Action description	Element/Peculiarity	Property
Stop HPSI pumps	OBJECT	HPSI pumps
	MEANS	INH
	ACCEPTANCE CRITERION	OBJ (dichotomous)
	CONSTRAINT	NL
	Peculiarity	SEL
Throttle HPSI flow	OBJECT	HPSI flow
	MEANS	NM
	ACCEPTANCE CRITERION	NC
	CONSTRAINT	NL
	Peculiarity	SEL
Operate PLCS	OBJECT	PLCS
	MEANS	INH
	ACCEPTANCE CRITERION	OBJ (dichotomous)
	CONSTRAINT	NL
	Peculiarity	SEL
Operate charging pumps	OBJECT	Charging pumps
	MEANS	INH
	ACCEPTANCE CRITERION	OBJ (dichotomous)
	CONSTRAINT	NL
	Peculiarity	SEL

6.3 Constructing Graphs

Based on the result of action decompositions as presented in Table 6.8, we are able to construct a set of graphs that characterize three kinds of complexity factors: (1) the amount of information to be processed by qualified operators, (2) the amount of domain knowledge that is indispensable to perform the required action, and (3) the level of engineering decision related to the establishment of an appropriate decision criterion to perform the required actions.

6.3.1 Information Structure Graph

The first graph we need to construct is one that is able to characterize the requisite information to accomplish the required actions. In other words, the amount of information to be processed by qualified operators should be represented by this graph. To this end, it is necessary to answer a preliminary question: *What kind of information should be managed to perform proceduralized tasks*? In connection with this question, it is to be noted that most qualified operators working in the MCR of PWRs have performed emergency tasks by using conventional control devices, such as push buttons, knobs, indicators, measurements about process parameters, trend recorders, and alarm tiles, etc. This means that the information to be managed by qualified operators can be expressed by the combination of five types of basic information shown in Table 6.9 (Lee *et al*. 2008).

Table 6.9 Basic information types in a conventional MCR

Basic type	Meaning	Canonical example
Boolean (B)	Qualified operators need to manage binary information	Identifying the existence of process alarms
	Qualified operators need to manipulate a component that has a binary operating mode	Manipulating a valve (open/close) or a pump (start/stop), etc.
Float (F)	Qualified operators need to manage the value of a process parameter presented by a real number	Reading pressure, temperature, flow rate, etc.
Integer (I)	Qualified operators need to manage the value of a process parameter presented by an integer	Indentifying the number of cooling fans under operation
Array of Boolean (AB)	Qualified operators need to manipulate a component that has several kinds of operating modes	Manipulating a valve or a pump having several operating modes, such as open, close, auto, etc.
Array of Float (AF)	Qualified operators need to manipulate a component that can be continuously adjusted	Manipulating a valve that can continuously adjust its open position
	Qualified operators need to determine the trend of a process parameter	Identifying the trend (increase, decrease, constant) of pressure, temperature, flow rate, etc.

In addition, it is believed that qualified operators can accomplish the required action more easily and correctly when they are given critical information compatible with the three radical elements of action specifications. As an example, let us consider *stop HPSI pumps* action. In this case, although there is no detailed description, qualified operators would be expected to already know appropriate controllers to stop HPSI pumps (i.e., *INH*). In addition, since there is no *CONTRAINT* in this action, qualified operators need to access information by which the stoppage of HPSI pumps can be directly confirmed. This implies that qualified operators have to manage at least two kinds of information related to (1) the manipulation of HPSI pump controllers (*MEANS*) and (2) the confirmation of desired states (*ACCEPTANCE CRITERION*). Accordingly, it is possible to construct the information structure graph (ISG) of this action, which corresponds to the data structure graph of software (Fig. 4.2). To clarify this aspect, it will be helpful to compare two kinds of arbitrary control environments as depicted in Fig. 6.2.

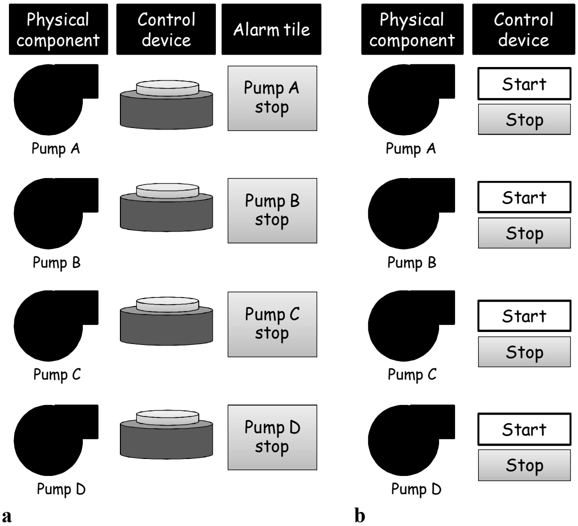
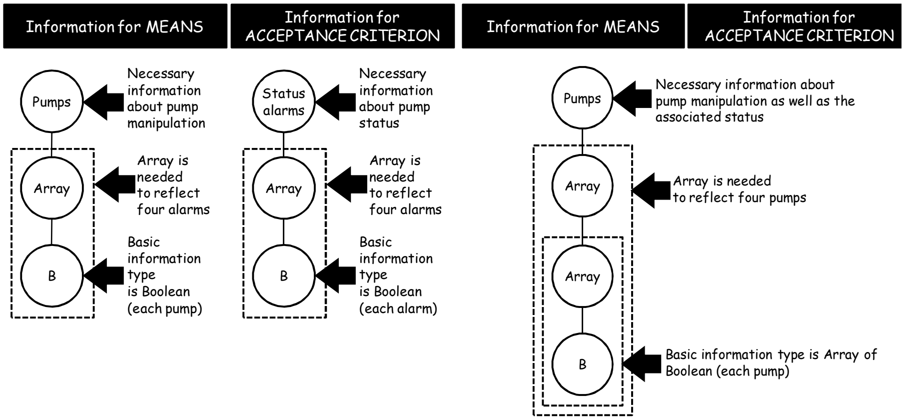


Fig. 6.2 Two kinds of arbitrary control environments

In Fig. 6.2a, the manipulation of each pump can be done by a push button that only has two operating modes (or functions), such as start or stop. In addition, there are four alarm tiles dedicated to informing qualified operators of the status of the pumps. In contrast, Fig. 6.2b shows four selection buttons that allow qualified operators not only to control the pumps but also to see their status. In other words, since a selected operating mode can be highlighted by a different color or blinking light, qualified operators easily identify the status of the pumps without accessing other sources of information (Lee et al. 2008).

Accordingly, even though qualified operators perform the same actions, different ISGs can be constructed due to the difference in control environments. That is, qualified operators who have to stop pumps in a control environment like that shown in Fig. 6.2a need to simultaneously manage two kinds of information, while those working in a control environment like that shown in Fig. 6.2b can accomplish the required action with a single source of information. Figure 6.3 shows two kinds of ISG that represent the amount of information to be managed by qualified operators.

It is not surprising that there are many required actions with the same source of information for a *MEANS* and an *ACCEPTANCE CRITERION*. For example, let us consider *verify pressurizer pressure is less than 123.9kg/cm^2* action.



ISG for Fig. 6.2a **ISG for Fig. 6.2b**

Fig. 6.3 Two kinds of ISG due to different control environments

In this case, although there is no description about the MEANS, it seems to be evident that qualified operators should access the pressurizer pressure indicator (i.e., *INH*). In addition, in order to determine whether the *ACCEPTANCE CRITERION* of this action is satisfied or not, qualified operators need to read the current pressurizer pressure value. This implies that the source of necessary information pertaining to the *ACCEPTANCE CRITERION* is also the pressurizer pressure indicator. Accordingly, the ISG of this action can be depicted as in Fig. 6.4.

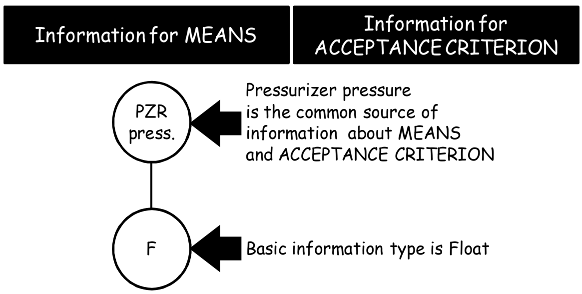


Fig. 6.4 ISG of an action that shares the same source of information about *MEANS* and *ACCEPTANCE CRITERION*

6.3.2 Abstraction Hierarchy Graph

Next, we have to construct a graph that can determine the amount of domain knowledge needed to perform the required action. In this regard, Moray (1998) pointed out that qualified operators usually accumulate domain knowledge in a hierarchical way.

> Thus, an operator may initially learn all the details of the controls in a control panel, but later come to think of them not as 'Valve 1, Valve 2, Pump 6,' etc., but as 'Cooling system,' Steam generator,' etc. This description in turn can be remodeled into 'Power Generation, Power distribution,' etc. Thus, operators construct a hierarchical set of models as a series of many-to-one mappings (p. 295).

In other words, qualified operators should start to build their domain knowledge from the component level to a higher level that consists of several components. In addition, over time, qualified operators will repeat the integration of a lower level knowledge in order to get a higher level knowledge. This strongly suggests that the amount of domain knowledge can be represented in the form of a hierarchical graph that is very similar to a software data structure graph.

With this in mind, we are able to adopt the framework of an abstraction hierarchy (AH), which was developed under the context of a supervisory control task (Rasmussen 1986). According to the AH framework, any human-made physical system can be analyzed by the following five levels of inherent functions.

- *Functional purpose* The intended functional effect of a system on its environment, such as the generation of electricity for NPPs.
- *Abstract function* The overall function of a system, which is represented by a causal structure such as mass or energy.
- *Generalized function* A set of basic functions that represent the functional structure of a system above the level of standard components.
- *Physical function* The characteristics of standard components, which can be clearly distinguished from their intrinsic functions, such as the function of pumps or valves, etc.
- *Physical form* The physical appearance of a component, such as its shape, weight, color, etc.

Based on these definitions, Rasmussen (1976, 1986) and Vicente (1999) emphasized that the AH framework is a remarkable tool for extracting the characteristics of domain knowledge to be considered by qualified operators. For this reason, it is expected that the AH framework can be used as a theoretical basis to identify the level of domain knowledge. Accordingly, as summarized in Table 6.10, four levels of domain knowledge are defined based on the results of a previous study (Jung 2001).

Table 6.10 shows that there are three differences between Rasmussen's AH framework and the four levels of domain knowledge. The first one is that domain knowledge corresponding to the *physical form* of the AH framework is excluded from the classification of domain knowledge because it was assumed that qualified operators would carry out proceduralized tasks. In other words, as stated in Sect. 3.2, since qualified operators have a minimum level of domain knowledge, it is believed that they would already have domain knowledge about the physical form of a component.

Table 6.10 Four levels of domain knowledge

Rasmussen's AH	Level of domain knowledge	Meaning
Abstract function	Abstract function (AF) related domain knowledge	Qualified operators need domain knowledge for delineating mass or energy flow based on two or more process functions or conditions
	Process function (PF) related domain knowledge	Qualified operators need domain knowledge for describing mass or energy flow based on two or more system functions or conditions
Generalized function	System function (SF) related domain knowledge	Qualified operators need domain knowledge that is related to two or more component functions or conditions
Physical function	Component function (CF) related domain knowledge	Qualified operators need domain knowledge that is related to the condition or function of a component, such as a valve, pump, heat exchanger and a heater, etc.

The second difference is the exclusion of domain knowledge related to the *functional purpose* defined in the AH framework. That is, it is futile to describe the required actions at the level of the functional purpose because such actions should provide qualified operators with detailed action specifications. In other words, *minimize the release of a radioactive material into the environment* action that describes one of the ultimate goals of EOPs is not helpful in providing detailed actions that qualified operators really want to know – *what is to be done* or *how to do it*.

The last difference is that domain knowledge pertaining to the *abstract function* of the AH framework has been subdivided into two levels, such as the *abstract function* and *process function* related domain knowledge. For example, let us consider two arbitrary actions: (1) *maintain core heat removal* and (2) *maintain the primary circulation*. According to the AH framework, both actions must belong to the abstract function level because they deal with the overall functions pertaining to the balance of mass and energy flow of PWRs (Sect. 5.1). However, these two actions seem to be distinguishable because the latter would be a subset of the former (i.e., one plausible way of maintaining core heat removal is to maintain the primary circulation). This strongly implies that qualified operators may need broader domain knowledge when the former action is called for. Therefore, to resolve this problem, the process function is introduced in Table 6.10. As a result, Fig. 6.5 shows an abstraction hierarchy graph (AHG) that can be used to represent the amount of domain knowledge needed by qualified operators.

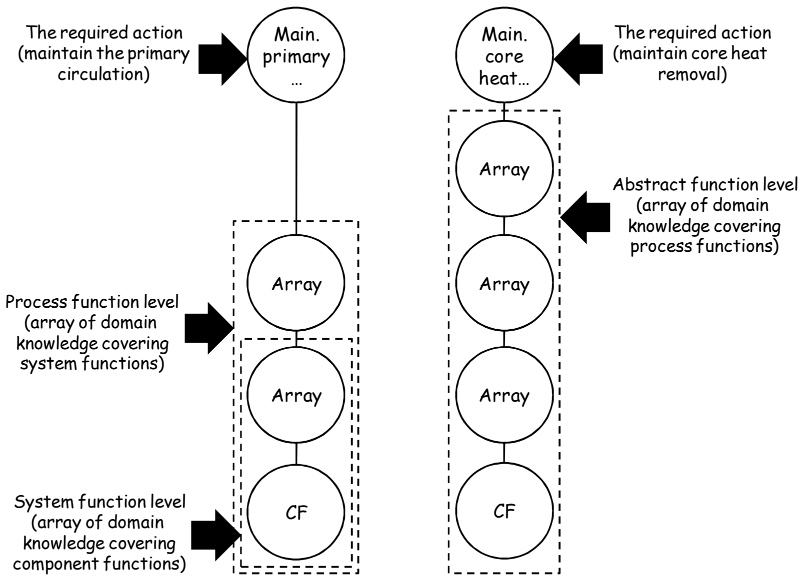


Fig. 6.5 AHGs of two arbitrary actions

6.3.3 Engineering Decision Graph

The last graph that we have to construct is related to the level of an engineering decision by which the amount of cognitive resources needed to establish the decision criteria of the required actions can be expressed. In this regard, although there is no explicit rule, it is assumed that qualified operators usually accomplish a task demanding a high-level cognitive activity by decomposing it into a series of subtasks demanding lower-level cognitive activities (Rasmussen 1976; Hollnagel 1993a). For example, Ullman and D'Ambrosio (1995) found that engineers decompose design problems into manageable subproblems. In addition, Shugan (1980) pointed out that the cost of thinking could be captured by a measurable (i.e., well-defined and calculable) unit of thought, such as the average cost per binary comparison. Similarly, Jiang and Klein (2000), Johnson and Payne (1985), Spence and Tsai (1997), and Todd and Benbasat (2000) commonly stated that any cognitive process can be represented by a sequence of elementary cognitive activities or skills, such as comparing and recalling, etc.

The above rationales strongly support the idea that the decomposition of a complicated task is practical problem-solving technique. Actually, Bainbridge (1997) asserted that "For example, the task goal "keep temperature 300°C," involves the cognitive goals "find current temperature," "evaluate actual against required temperature," "choose corrective action." These steps may not be consciously explicit or distinct to the person doing the task (p. 355)."

This indicates that the level of engineering decision can be represented in the form of a hierarchical graph, in which the required action demanding a higher-level engineering decision is regarded as a series of actions demanding lower-level engineering decisions. To this end, it is indispensable to establish a technical basis by which the level of the engineering decision can be properly distinguished. In light of this concern, it would be very helpful to introduce a decision ladder model developed by Rasmussen (1974) because it depicts the decision making process of qualified operators who are dealing with a supervisory control task. Figure 6.6 shows the overall structure of the decision ladder model.

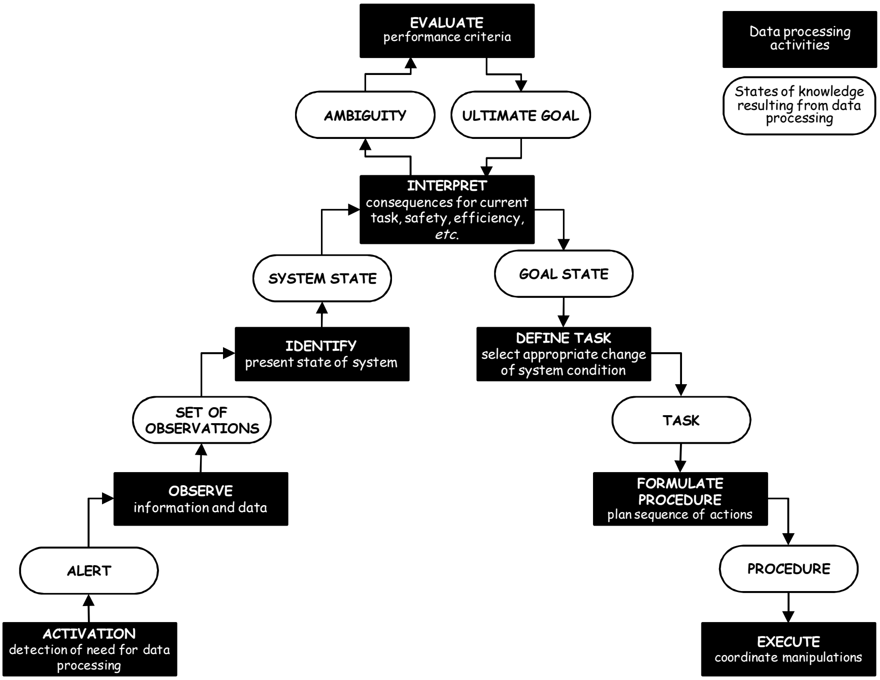


Fig. 6.6 The decision ladder model (see p. 27 of Rasmussen 1974)

Here, it should be noted that we need to be aware that the decision ladder model needs to be simplified when there is a procedure to be followed by qualified operators because of two reasons. First, since qualified operators already know what needs to be done, the *ACTIVATION* activity (i.e., detection of need for data processing) is less meaningful. Second, in most cases, qualified operators do not need to formulate the sequence of actions by themselves, because proceduralized tasks already have a predefined sequence of actions. As a result, Fig. 6.7 illustrates the simplified version of the decision ladder model.

From the simplified decision ladder model, it is possible to classify four levels of engineering decision pertaining to the performance of proceduralized tasks. To this end, let us consider an arbitrary system depicted in Fig. 3.2 with four arbitrary actions listed in Table 6.11.

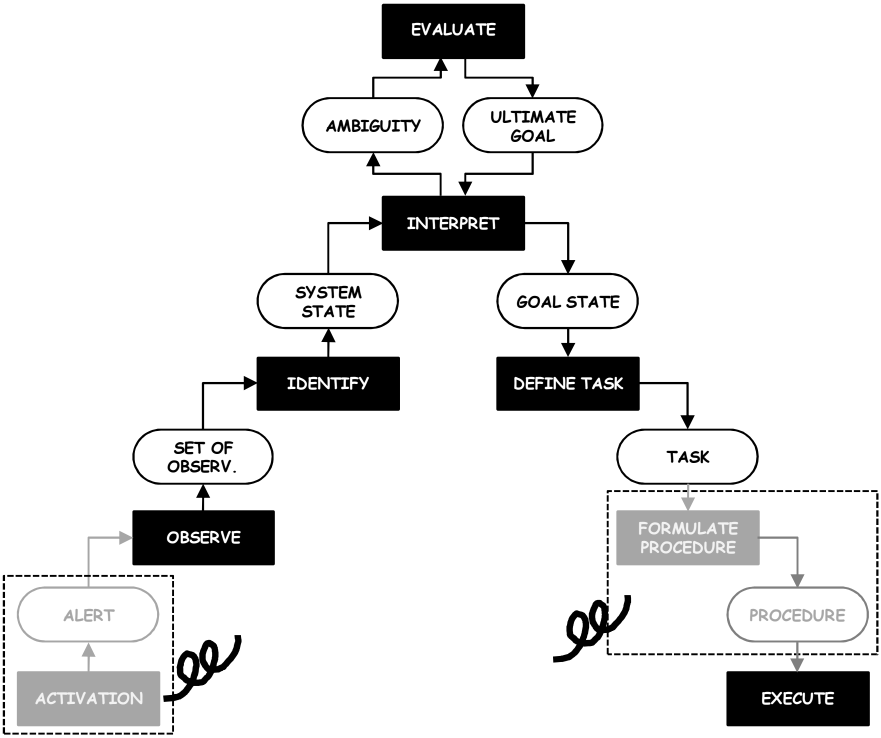


Fig. 6.7 Simplified decision ladder model to deal with a special situation in which qualified operators have to follow proceduralized tasks

Table 6.11 Four arbitrary actions to explain the levels of the engineering decision

ID	Action description
1	Verify the water level of Tank 1 is less than 30%
2	Verify the water level of Tank 1 is decreasing
3	Verify the water level of Tank 1 is abnormally decreasing
4	If necessary, perform any of the following. • Increase outflow • Provide bypass line

First of all, when qualified operators faced with *verify the water level of Tank 1 is less than 30%* action, they will start this action by observing the water level of Tank 1, because this is probably essential information to decide whether the water level of Tank 1 is less than 30% or not. Then, qualified operators will make a decision by comparing the observed water level with the *ACCEPTANCE CRITERION* of this action. From the point of view of the decision ladder model, a plausible sequence could be illustrated as Fig. 6.8.

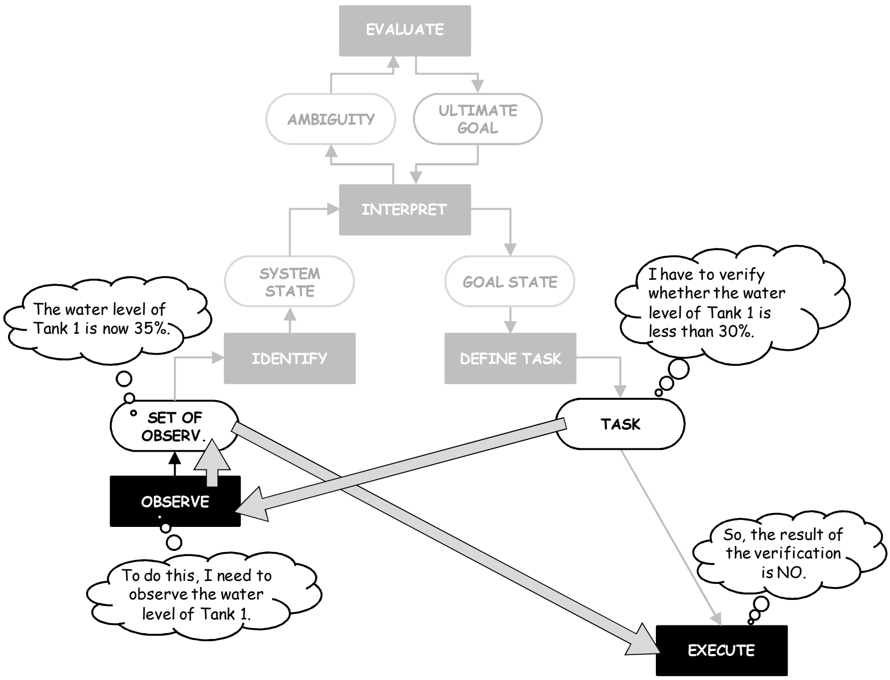


Fig. 6.8 Example explaining the sequence of decision making activities when qualified operators need to carry out *verify the water level of Tank 1 is less than 30%* action

Second, in order to perform *verify the water level of Tank 1 is decreasing* action, qualified operators will start this action by observing the water level of Tank 1. They will also realize that they have to keep observing the water level of Tank 1 for a while (i.e., collecting data about the water level with respect to time). Based on the collected data, they will identify the state of Tank 1, then they will finally make a decision about whether the water level is falling off or not. Figure 6.9 represents the plausible sequence of the associated decision making activities based on the simplified decision ladder model.

As shown in Fig. 6.9, it is expected that qualified operators will identify the state of Tank 1 by a set of data related to the changes of the water level over a time. This indicates that, as mentioned at the beginning of this section, it is possible to think of a state identification as a combination of lower-level cognitive activities, such as repeated *OBSERVE* activities. For this reason, a symbol signifying a circulation is inserted in the *OBSERVE* activity in Fig. 6.9.

Third, if qualified operators have to perform *verify the water level of Tank 1 is abnormally decreasing* action, then they will carry out a series of decision making activities that are similar to those related to *verify the water level of Tank 1 is decreasing* action. However, it is assumed that qualified operators will have to additionally perform the *INTERPRET* activity as illustrated in Fig. 6.10.

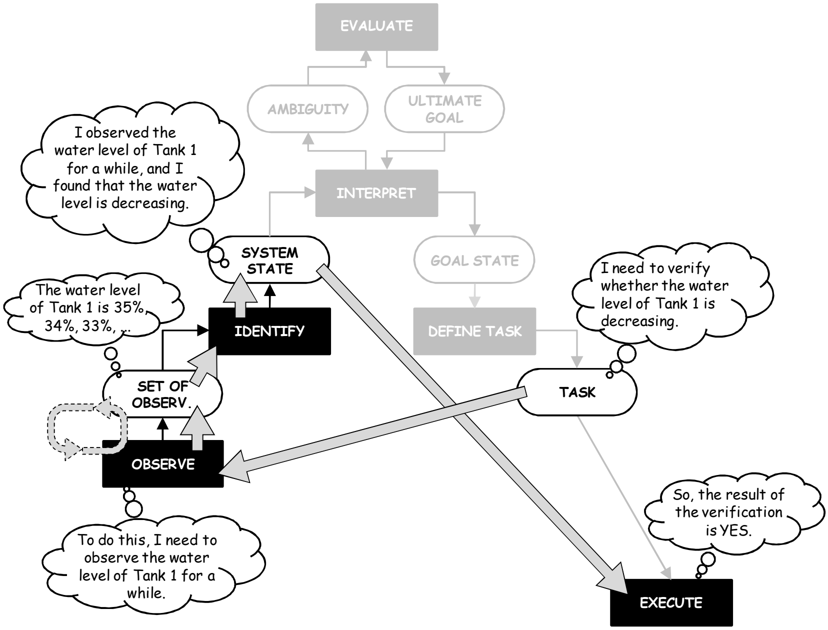


Fig. 6.9 Example of the sequence of cognitive activities pertaining to *verify the water level of Tank 1 is decreasing* action

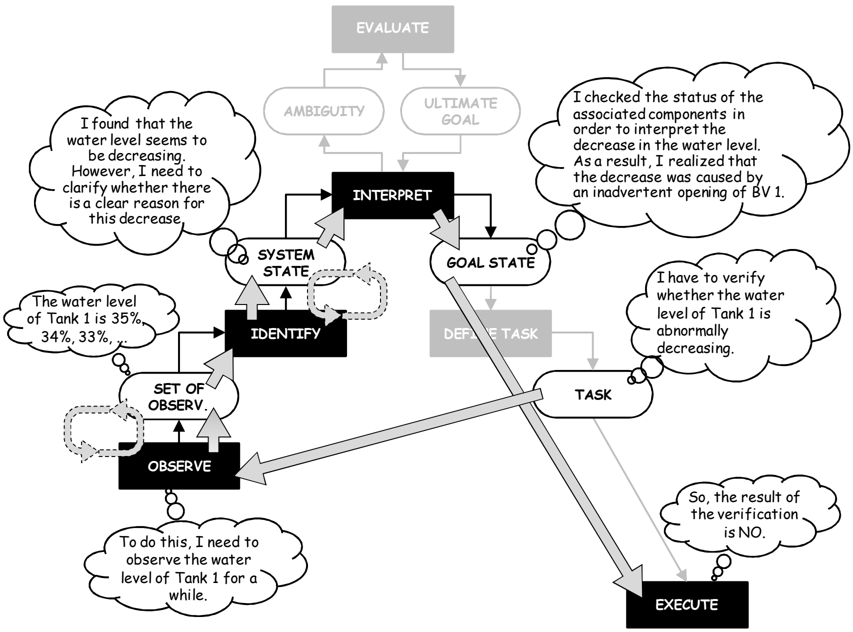


Fig. 6.10 Example of the sequence of decision making activities related to *verify the water level of Tank 1 is abnormally decreasing* action

As can be seen from Fig. 6.10, when the water level of Tank 1 seems to be decreasing, qualified operators have to decide whether or not this tendency can be explained. In other words, if there is a clear reason why the water level is decreasing, this symptom would be regarded as a normal response. In contrast, if there is no probable cause, then qualified operators will decide that the water level of Tank 1 is abnormally decreasing due to other reasons, such as a break in a pipe.

In order to make this kind of determination, qualified operators may repeatedly collect supplementary information such as the status of components that are able to cause a decrease in the water level of Tank 1 (e.g., the state of BV 1 as well as BV 2 or the open position of CV 1). For this reason, a symbol signifying circulation is inserted in the *IDENTIFY* activity. In addition, it is assumed that the *INTERPRET* activity could be expressed as a series of lower-level cognitive activities (i.e., the repetition of *IDENTIFY* as well as *OBSERVE* activities).

The last action that we need to scrutinize is one that forces qualified operators to select the most appropriate action from among several alternatives (Fig. 6.11).

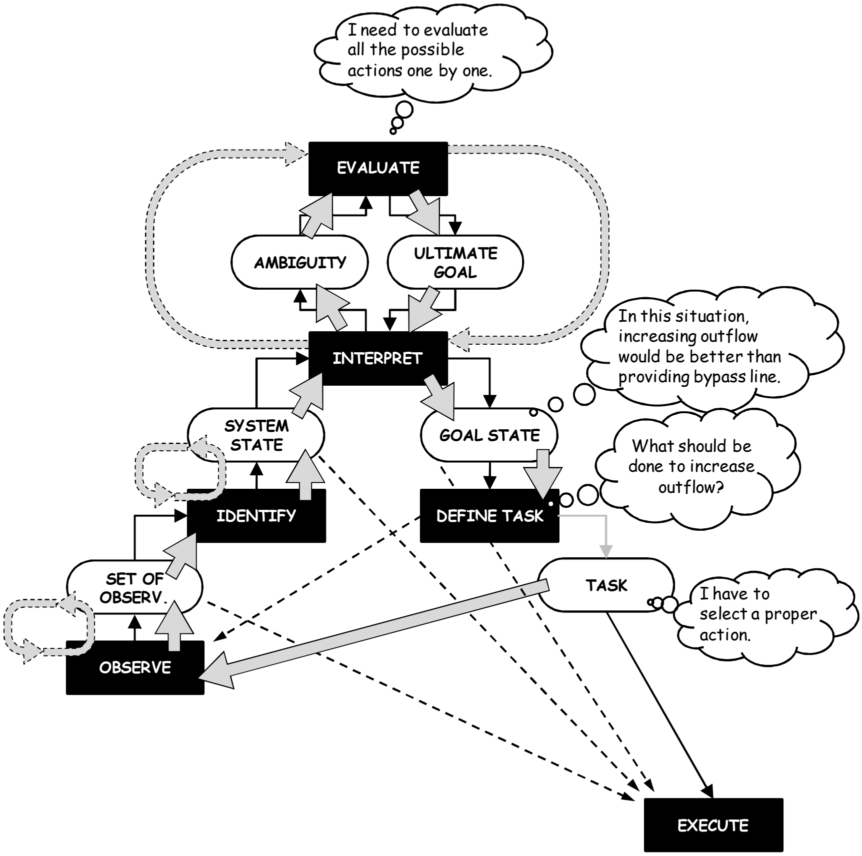


Fig. 6.11 Example of the sequence of decision making activities when qualified operators must select the most appropriate action

Let us recall the fourth action shown in Table 6.11. When qualified operators need to perform this action, they will carry out several activities (i.e., observing necessary information, identifying the state of a related system, etc.) in order to determine whether each alternative is practicable or not in an ongoing situation (e.g., considering the readiness of the associated components or equipment, etc.). Unfortunately, if two or more alternatives are equally probable, then qualified operators should repeatedly evaluate the pros and cons of all possible alternatives. Accordingly, one of the plausible decision making sequences related to the selection of an appropriate action would be illustrated as in Fig. 6.11.

Here, it should be noted that qualified operators have to make one of the three engineering decisions after the selection of an appropriate action. For example, when qualified operators decide that increasing outflow would be better than providing a bypass line, they need to start considering an additional engineering decision to clarify how to increase the outflow. Accordingly, several dotted lines are used in Fig. 6.11 to depict a set of decision making activities related to the performance of the selected action.

In light of the above explanations, we can now characterize engineering decisions. Table 6.12 summarizes the four levels of engineering decisions with the associated meanings. It is to be noted that an action that forces qualified operators to carry out a continuous control is classified as a third level engineering decision (ED-3), because qualified operators need to continuously monitor the satisfaction of an *ACCEPTANCE CRITERION* through the repetition of *IDENTIFY* and *OBSERVE* activities.

Table 6.12 Four levels of engineering decision

Level*	Meaning	Typical action
ED-1	An action that can be accomplished by a simple decision with a clear criterion	Verify the water level of Tank 1 is less than 30%
ED-2	An action that forces qualified operators to integrate lower-level information to create higher-level information	Verify the water level of Tank 1 is decreasing
ED-3	An action that forces qualified operators to identify situations or conditions based on several process parameters, symptoms, and the associated knowledge	Verify the water level of Tank 1 is abnormally decreasing
	An action that forces qualified operators to carry out a continuous control	Maintain the water level of Tank 1 within a range of 23.5% - 50%
ED-4	An action that forces qualified operators to select a proper action	If necessary, perform any of the following. …

*ED: engineering decision.

Based on the above rationales, we can construct an engineering decision graph (EDG) that can be used to characterize the amount of cognitive resources needed to establish the decision criteria of the required actions. For example, Fig. 6.12

depicts EDGs for the first and fourth actions listed in Table 6.11.

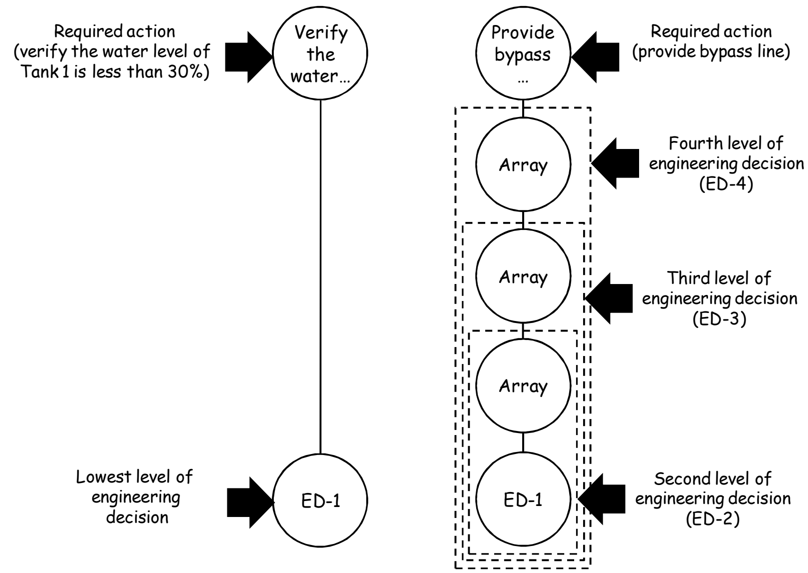


Fig. 6.12 EDGs of two arbitrary actions

As shown in Fig. 6.12, it is assumed that the performance of an action pertaining to ED-2 can be represented by a series of lower level actions (i.e., *array of ED-1*). Similarly, an action related to ED-3 can be expressed by a series of actions belonging to ED-2.

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