Chapter 2
Controlling Complex Technical Systems: The Control Room Operator's Tasks in Process Industries

2.1 Setting the Scene

If you enter a control room, the quietness is something you will notice first. The work in control rooms during routine operations is silent. After you shut the door, the sounds of producing steel, food, or pharmaceutical products, refining oil, or producing energy are kept outside. The tranquillity of the atmosphere is intensified by the shaded atmosphere of the room, in which PC screens flicker in black, blue and green, showing filigree displays of pipes, valves and numbers. Workers alone, in pairs or in teams watch the displays arranged on one, two, three or more screens in a focused manner, talk to each other in soft tones, pointing to a certain part of the displayed plant, moving the computer mouse to a detail, perhaps altering a value. In most control rooms I have visited, the outside world, the outside weather, the technical construction of the production process, the converted materials, the physical, chemical or biological process steps as well as the workers operating the plant are viewed through the lens of the PC screens (Fig. 2.1).

On the surface, the job of a control room operator in routine situations does not appear to be very spectacular. Compared to jobs which have been examined over the last century by industrial psychologists and human factors and ergonomics specialists, which emphasise physical ergonomics (anthropometric, biomechanical, physiological factors, factors related to posture such as sitting and standing, manual handling of material), a control room is clean, silent and tidy, and the work in a control room does not require hard physical labour or coping with heat, cold, dangerous substances, assembly line pace-based time pressure or motor dexterity. Nevertheless, process control plants are assumed to notably challenge human factors research (Moray 1997).

A control room can be defined as a location designed for an operator to be in control of a process (Hollnagel and Woods 2005). In the case of process industries, the location is a physical room in a physical building (in contrast to a cockpit that is moving). *The meaning of control in this context is to minimise or eliminate unwanted process variablities*; the process is a continuous activity. The process

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Fig. 2.1 Control room at German NPP (Photo courtesy of GfS/KSG, Essen, Germany)

has its own dynamics and hence changes if left alone (Hollnagel and Woods 2005). The control room is a room with a view to the past, present and the future (Hollnagel and Woods 2005). The view to the past is necessary to understand the current situation, to build up expectation, and to anticipate what may lie ahead (Hollnagel and Woods 2005)

Vicente's (2007) and Vicente et al.'s (2004) description of a control room of a Canadian NPP is a rather representative example of a control room in general. The control room for the plant has four control units (each controlling its own reactor). The single operator runs a unit together with other personnel serving support roles. Each control unit occupies a demarcated workspace within a single, large room that is completely open and has no barriers to visibility. The operator of each unit can see the panels and alarms of all other units, allowing him/her to follow and monitor activities on other units and maintain an overall awareness of plant activity (Vicente 2007, p. 91). An example of a German NPP that illustrates Vicente's descriptions (2007) is displayed in Fig. 2.2.

Not only in an NPP control room but also in control rooms in refineries, the units include control panels, an operator desk with one or more telephones, a printer, and bookshelves upon which to place procedure documents and other operation documents. Alarms are presented on computer screens, which light up and provide an audio signal (buzzer) if an alarm condition occurs. In many control rooms, an operator monitors 3–4 screens placed on his desk, on which physical schematics, trend displays, and bar chart displays etc. are presented. In some systems, screens show 1,000 detailed displays and 20 system-oriented overview displays (Veland and Eikas 2007).

What do control room operators control? As introduced above, control room operators control material and energy flows, which are made to interact with and

Fig. 2.2 NPP control room in Germany (Photo by GfS/KSG, Essen, Germany), because the room is windowless, the control room teams have hung up a poster with the outside view (in the back). Files with standard operating procedures on the shelves

transform each other. By means of physical or chemical transformation, the “process control industry” incorporates the continuous and batch processing of materials and energy in their operations (Moray 1997). “Examples include the generation of electricity in conventional fuel and nuclear power plants, the separation of petroleum by fractional distillation in refineries into gas, gasoline, oil, and residue, hot strip rolling in steel production, chemical pulping in the production of paper; pasteurization of milk, and high pressure synthesis of ammonia” (Woods et al. 1987, p. 1726). A comprehensible overview of the process industries is provided by Austin (1984) and further below (Sect. 2.2.2).

2.2 Defining the Term “Complex” in a Complex Technical System

Continuous process systems are physically large, covering many hectares (e.g. Fig. 2.3) and are named as complex technical systems. As will be outlined further below in more detail, the process industries range from continuous facilities in the petrochemical industry to large-batch manufacturing in steel production and glass manufacturing, to small-batch manufacturing in the food and pharmaceutical industry (van Donk and Fransoo 2006).

A system can be defined as a collection of components that act together to achieve a goal that could not be achieved by any single component or part alone (Proctor and van Zandt 2008, p. 569; Walker et al. 2010).

Fig. 2.3 Coker plant in the Gelsenkirchen Horst refinery at night, http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/images/raffinerie_verarbeitung/raffinerie_nacht.jpg (retrieved April 8th 2013)

The "technical" aspects include the technological component (Emery 1959), e.g. material, machines that convert inputs (e.g. raw material) into outputs (e.g. heat, gas, products) as well as territory which are "belonging" to the organisation (Emery 1959).

According to Perrow (1984), systems are divided into four levels of increasing aggregation:

- parts (e.g. a valve, the smallest component of a system),
- units (e.g. a steam generator, functionally related collection of parts),
- subsystems (an array of units, such as a steam generator and the water return system including condensate polisher and motors, pumps, and piping – the secondary cooling system) and
- systems (including many subsystems, e.g. the complex NPP or refinery, Perrow 1984, p. 65).

In particular, the process of a continuous process system (e.g. a chemical plant or refinery) is additionally geographically widely distributed (e.g. in contrast to a cockpit), with subsystems and components spread over great distances in three dimensions involving hundreds of variables (Moray 1997). *But what specifically constitutes a "complex" system?* The complexity of a system is defined as "the number of elements and relations of a system" (Fischer et al. 2012, p. 22; Funke 1985). The number of elements and relations within a technical system can be more precisely characterised in terms of element interactivity/interconnectivity, dynamic effects, non-transparency, multiple goals (Brehmer and Dörner 1993; Funke 1985; Kluge et al. 2008; Sterman 1994), and social complexity (Dörner 1989/2003; Table 2.2).

The process to be controlled typically consists of a large number of interrelated and cross-coupled variables (Moray 1997; Vicente 2007; Wickens and Hollands 2000), meaning that various aspects of a situation are not independent and therefore cannot be independently influenced, a characteristic called **interconnectivity** (Kluge et al. 2008). Interconnectivity also stresses the importance of recognising unfamiliar and unintended feedback loops (Perrow 1984), control parameters with potential interactions and undesired and desired “parallel effects” (Blech and Funke 2005). Parallel effects are caused by ramified cause-and-effect chains, initiated by altering only one single input variable at the beginning of the chain (Kluge et al. 2008). Perrow (1984) calls this phenomenon a complex interaction in which one component can interact with one or more components outside of the normal production sequence, either by design or not by design. Complex interactions as they affect the operators are those “unfamiliar sequences of unplanned and unexpected sequences and either not visible or not immediately comprehensible” (Perrow 1984, p. 78).

In addition to parallel effects, variables can change dynamically in terms of their own state, which is called **dynamic effects** (Kluge et al. 2008; Sterman 1994; Walker et al. 2010). These dynamic effects play a role, for example, in heat generation, for instance in terms of the residual heat in an NPP, or whenever one speaks of an “uncontrolled reaction”. Somewhat less dramatic effects are found, for example, in the form of weather influences, when the technical plant parts heat up strongly with strong heat in the summer. Additionally, the dynamic effects are caused by the continuous process, in which materials continuously flow through the plant, for example in board mills, chemicals, oil, electricity, food production, or glass production (Crossman 1974). In some continuous process systems, such as electricity generating plants and petrochemical plants, dynamics and time delays are extreme, as it may take many hours or even days to start up (Moray 1997).

The technical process which is responsibly monitored and controlled by the operator is controlled by technical monitoring devices, precisely because of the tremendous complexity of the process, hazardous environments in which they take place and toxic materials which are employed (Wickens and Hollands 2000). Due to the automation, the complex technical systems to be controlled are characterised by **non-transparency** for the operator, which means that neither structure nor dynamics are fully disclosed to the operator’s senses (Funke 2010). The control room operator’s task is therefore also called centralised remote control (Crossman 1974). The operations being controlled are inaccessible to the operator and are handled in an artificial setting such as the control room. Due to the hazards associated with, for example, high levels of radiation and the potential consequences of even small accidents, the personnel in NPP are rather remote from the physical process (Figs. 2.4, 2.5, and 2.6.), whereas in steel production, for example, parts of the plants are still directly accessible to human senses in that they are observable and audible. An NPP control room (as in Fig. 2.1.) is isolated from the physical process that is being controlled (Gaddy and Wachtel 1992). Control is exercised by switches and buttons and telephones are used to communicate with the field operators in the plant (Moray 1997), while current technical developments also allow for the usage of head-mounted displays for communication and knowledge

Fig. 2.4 Photo of a control room in a steel plant (with window) control room at HKM (Hüttenwerke Krupp Mannesmann) (Photo courtesy of HKM Duisburg)

sharing (Grauel et al. 2012) between control room operators and maintenance personnel in the plant for collaborative troubleshooting.

In contrast, the control rooms for controlling continuous casting in the steel industry are much closer to the production process, which is extremely hot, noisy and dangerous for the workers, and which is not under moment-to-moment manual control. Along the length of the process, there are a series of local control stations for different tasks along the line (Moray 1997) and operators can directly see the casting process and the molten steel. There is a subordinate control room considerably above the floor of the plant enabling the controller to directly inspect/oversee the entire plant through its window (Figs. 2.4 and 2.5). In Fig. 2.6, the window does not allow the process to be monitored, but does allow the outside weather conditions to be monitored in order to be able to proactively consider weather impacts on the process.

The more the control room is isolated from the plant to be monitored and controlled, the more the operator has to rely on the information presented by the screens and displays. Non-transparency, as in the case when operators are isolated from the operations being controlled, is also due to the keyhole effect (Woods et al. 1990; Woods 1984). The operator might get lost in the large number of (up to thousands) of displays which he/she is able to call up, rendering him/her unable to maintain a broad overview, and becoming disoriented, fixated or lost in the display structure (Kim and Seong 2009; Woods et al. 1990).

Fig. 2.5 Example photo of a control room in a steel plant (HKM) with window, casting operation HKM (Photo courtesy of HKM Duisburg)

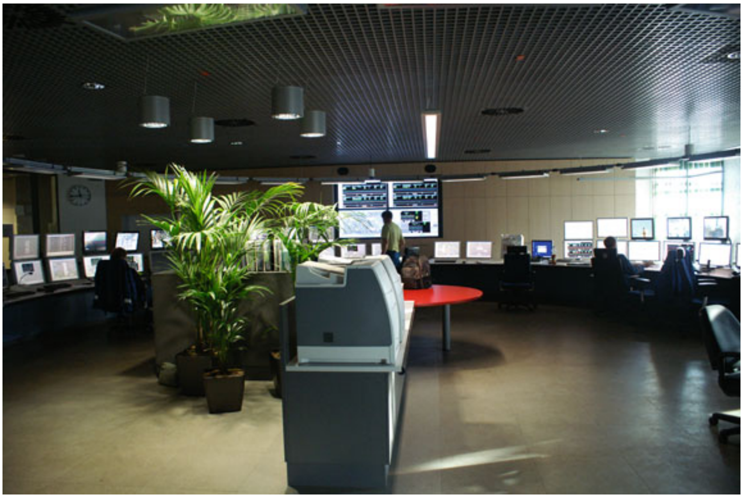

Fig. 2.6 Control room at BP Gelsenkirchen/Ruhr Oel GmbH (Photo courtesy of BP Gelsenkirchen/Ruhr Oel GmbH)

Accordingly, non-transparency is expressed through the fact that the chemical, physical or biomechanical processes which are controlled cannot be easily visualised. This means that, as described above, the control room operator (a) perceives only a limited number of the parts of the plant, and (b) these are mediated by a Human Machine Interface (HMI) that informs the operator about the states of the plant. Only part of the relevant information is made available to an operator, who is controlling the 'outer-loop' variables, for example sets a set point of a desired temperature of blast furnace, whereas automated feedback loops control the 'inner loop', for example provides the amount of energy to the furnace required to reach the desired temperature (Wickens and Hollands 2000). The operator monitors the result produced by the automated process, adjusts the set point as required and may "trim" the control characteristics for optimum efficacy (Crossman 1974).

Additionally, the automated process might also be non-transparent in itself. Although some process control plants include rather simple operations such as baking or pasteurisation, with more transparent processes, other industrial systems are the most complex (interconnected, dynamic) ever built, in which physics and chemistry are only imperfectly understood and in which unforeseen events can therefore occur under special conditions of abnormal operations, with the risk of potentially catastrophic releases of toxic material and energy (Moray 1997, p. 1945; Perrow 1984).

With regard to non-transparency in terms of the physical visibility of the process, the process in an NPP is the least visible, followed by petrochemical refineries and steel production, which is assumed to be more visible compared to the other two (Moray 1987).

The **combination of dynamic effects and non-transparency** is also apparent in that the process variables that are controlled and regulated are reacting slowly and have long time constraints (Wickens and Hollands 2000), leading to delayed feedback with regard to the actions taken by the operator. The *control action taken may not produce a visible system response* for seconds or minutes. In contrast, dynamic effects and non-transparency can be become immediately apparent in cases in which a warning indicates the existence of a system failure. The *warning can quickly lead to an exponentially growing number of hundreds of subsequent warnings* which – although they transparently indicate a problem – taken together will lead to non-transparency in the current moment. As outlined by Wickens and Hollands (2000), from the operator's point of view, one warning alone is often not interpretable: "This unfortunate state of affairs" (Wickens and Hollands 2000, p. 530) occurs due to the vast interconnectedness that one primal failure will drive conditions at other parts of the plant out of their normal operating range so rapidly that within seconds or minutes, scores of warning lights and buzzers create a buzzing-flashing condition. A severe failure in an NPP can potentially cause 500 annunciators to change status in the first minute and more than 800 within the first 2 min (Wickens and Hollands 2000).

Additionally, the human operator must simultaneously pursue **multiple and even contradictory objectives**, so-called conflicting goals, such as achieving production and safety goals in parallel (Kluge et al. 2008; Reason 2008; Verschuur et al. 1996; Wickens and Hollands 2000). A human operator in a control room is confronted with a number of different goal facets to be weighted and coordinated (Funke 2010). As Crossman (1974) formulates, what the operator is trying to achieve is what the management wants him/her to achieve and represents the characteristics of multiple goals. The operator

- has to keep the process running as closely as possible to a given condition (regulation or stabilisation),
- has to adjust the process to give the best results according to criteria such as yield, quality, minimum use of power, least lost time (optimisation),
- has to avoid breakdowns as far as possible,
- has to regain normal running as soon as possible, and minimise loss of material or risk of serious damage if a breakdown has occurred (Crossman 1974, p. 7).

With regard to conflicting goals, Hansez and Chmiel (2010) address the general problem that production and safety are often not valued equally in practice, for example "the visibility of production over safety, imbalances in the resources allocated to each, and the rewards available, such as praises or bonuses for achieving production targets" (Hansez and Chmiel 2010, p. 268). Especially when the pressure for production is on, there is potential for safety to be compromised. Particularly in cases of non-routine/normal and abnormal situations (see below), the operator is faced with the choice of what do to, taking three not always compatible goals into consideration (Wickens and Hollands 2000):

1. Actions have to ensure system safety,
2. Actions should not jeopardise system economy and efficacy,
3. Actions should be taken that localise and correct the fault.

Goals might be incompatible because, for example, taking a plant off line to ensure safety will lead to a potential sacrifice of economy, mainly because of a costly loss of production while the plant is offline and a costly start-up of the plant after a shutdown to localise the failure correctly and in a timely manner.

This shows that the growing technological potential is seized upon and exploited to meet performance goals or efficiency pressures (Hollnagel and Woods 2005), for example reduced production costs and improved product quality. But, once the technology potential is exploited, this generally leads to an increase in system complexity, subsequently leading to increased task complexity (Hollnagel and Woods 2005; Perrow 1984). Increased system complexity together with an increased task complexity results in more opportunities for malfunctions and more cases in which actions have unexpected and adverse consequences (Hollnagel and Woods 2005). Additionally, the striving for higher efficiency brings the system closer to the limits of safe performance, which leads to a higher risk. In turn, higher risks are countered by applying various kinds of automated safety and warning systems, which in turn again lead to an even greater risk (Hollnagel and Woods 2005).

Finally, in many HROs, small crews are responsible for overall system operations, in terms of controlling multiple systems and decision making concerning system functioning (Carvallo et al. 2005; Reinartz 1993; Reinartz and Reinartz 1992; Vicente et al. 2004). In continuous process systems too, these systems are controlled by multiple agents such as the control room operators, plant floor

Fig. 2.7 Field operators discussing issues with the control room crew (Photo courtesy of BP Gelsenkirchen/Ruhr Oel GmbH)

Fig. 2.8 BP employee in the Emsland crude oil refinery on his tour during the nightshift, http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/images/presse/raffinerie_verarbeitung/23_imagebroschuere.jpg (retrieved April 8th 2013)

workers, maintenance workers, foremen, supervisors, managers (Moray 1997; Roth and Woods 1988; Woods et al. 1990) and workers from external companies and suppliers. For example in NPP, "Control room crews have the ultimate responsibility for daily operation, never perform work alone in the control room, and coordinate the immediate response to emergency situations" (Gaddy and Wachtel 1992, p. 383). NPP control room crews (each unit has five to six crews) are

Table. 2.1 Plant operations team roles (Based on Bullemer et al. 1997)

Team role	Description
Console operator	Is responsible for controlling the process via the DCS, monitors and controls plant, responsible for coordinating the actions of field operators, keeping abreast of the maintenance activities in the field. He/she is the focal point of communication between various distributed operations personnel throughout the complex task because he/she has the central view and control via the DCS.
Field operator	Responsible for his/her own plant area, often also qualified for other areas (to rotate between areas and monitor other areas), supports maintenance activities in the field, serves as human sensor, who checks or validates the correctness of the sensors, to ensure the view of the process is accurate. They identify potential problems with the process equipment, initiate preventive maintenance, take periodic product samples, prepare and warm up equipment, are responsible for directing maintenance personnel to the appropriate worksite. In a disturbance, they are the first "on the scene" and provide a critical diagnosis and mitigating response role in disturbance situations management by assessing the situation (e.g. confirming/refuting DCS data) or by taking actions (e.g. fire fighting); he/she can also support the console operator with assistance.
Shift leader	Is responsible for overseeing the field and console operator in the detailed monitoring of the process and ensuring the execution of the relevant preventive maintenance (daily routine duties), is a senior operations staff member, also in charge of the field, e.g. noting equipment problems and verifying sensor readings, responsible for filling out shift log book, during non-routine/normal and abnormal situations, shift leader supports console operator and calls for backups.
Operations superintendent	Responsible for productive and safe operations of the complex (complex is typically run by multiple shift teams); responsibilities: Monitoring and reporting of budget and costs, safety reporting and documentation, environmental compliance, incident reporting, training, production reporting to upper plant management, tracking and meeting higher-level plant objectives.
Shift coordinator	Plays the role of operation teams coordinator and management interface between operations superintendent and operations staff.
Site planner	Responsible for tracking possible market opportunities (e.g. high demands, high price, scheduled shipments, weather conditions) that may arise along with planning maintenance and turnarounds.
Process engineer	Responsible for generating daily production orders for each process unit (developed by site planner), troubleshoots process unit problems.
Control engineer	Maintains control tuning, objectives and develops improved control, often troubleshoots process and control-related problems after operations have been stabilised by operators.
Maintenance coordinator	Responsible for coordination of maintenance activities for plant units, coordinates periodic preventive maintenance and requests put in by operations team, orders material, determines whether contractors need to be hired
Maintenance technician	Responsible for maintaining and repairing all process equipment.

DCS distributed control system

comprised of two licensed senior reactor operators, one of whom is the supervisor, and two licensed reactor operators who share the duties of monitoring and controlling the plant (Gaddy and Wachtel 1992, p. 383). Additionally, a shift technical advisor with an engineering background is available but is not directly involved in the team (Gaddy and Wachtel 1992, p. 383).

Control rooms are therefore called multi-agent systems (Woods et al. 1990). Consequently, added to the features of technical complexity described so far is the complexity of relationships, which is called social complexity (Dörner 1989/2003) or **crew coordination complexity**, which results from the interconnectedness between multiple agents through coordination requirements. The dynamic control aspect of the continuous process is coupled with the need to coordinate multiple highly interactive processes imposing high coordination demands (Hagemann et al. 2012; Roth and Woods 1988; Waller et al. 2004).

A high level of communication between the multiple agents is required to coordinate activities and to avoid working at cross purposes (Roth and Woods 1988, p. 54; Stachowski et al. 2009, see Fig. 2.7). The human operators who are responsible for separate but strongly coupled units of the plant also need to be aware of their own actions with regard to the consequences they will bring about in another operator's units. Breakdowns in coordination across these units of responsibility may contribute to unnecessary trouble, near shutdowns or complete shutdowns (Roth and Woods 1988, p. 59).

If one looks, for example, at refineries, the console operator, who is controlling the process via the distributed control system (DCS), works as a team member in a plant operation team (Bullemer et al. 1997). The plant operation team in refineries and petrochemical plants consists of several plant roles as listed in Table 2.1. A prototypical operations shift team consists of a shift leader, a console operator, and two to five field operators (Bullemer et al. 1997). During the weekdays, many maintenance projects are going on, and the engineers, craftsmen, and management personnel are all available to interact with the shift team.

2.2.1 A Definition of a Complex Technical System

To sum up, the characteristics of a complex technical system are listed in Table 2.2. A complex technical system is characterised by the interconnectedness of a large number of variables and system parts, in which variables can change dynamically in terms of their own state, and in which structure and dynamics of the system are only partly disclosed to the operator (non-transparency), who is confronted with multiple goals that need to weighted and coordinated (conflicting goals), and who has to coordinate his/her activities with other interconnected agents (crew coordination complexity).

Table 2.2 Overview of constituent characteristics of complexity in complex technical systems

Characteristic	Definition and example
Element interactivity/ Interconnectedness	Various aspects of a situation are not independent and therefore cannot be independently influenced, e.g. the interplay of several subunits
Dynamics	Variables can change dynamically in terms of their own state, e.g. high outside temperatures heat the plant up in a deflagration, residual heat of fuel rods
Non-transparency	Structure and dynamics of the system are not fully disclosed to the operator, e.g. because the operator is isolated from the physical/chemical process and/or the process cannot be easily visualised e.g. a single warning can quickly lead to an exponentially growing number of hundreds of subsequent warnings, which taken together will lead to non-transparency, e.g. process variables that are controlled and regulated are reacting slowly and have long time constraints, meaning that the control action taken may not produce a visible system response for seconds or minutes
Multiple/conflicting goals	The operator is confronted with a number of different goal facets to be weighted and coordinated e.g. achieving production and safety goals in parallel
Crew coordination complexity	Interconnectedness between multiple agents (control room operators, field operators, plant floor workers, maintenance workers, foremen, shift supervisors, managers, in the case of an accident also firemen, first responder team, government, journalists) imposes high coordination demands

What does this mean for skill and knowledge acquisition?

The constituents of a complex technical system are relevant for deriving knowledge requirements as training objectives. These knowledge requirements take the form of mental models. Control room operators need a mental model representing the interconnectedness and dynamics of parts, units, and sub-processes (process mental model), the equipment to manage the process, for example automation and its displays, and the extent of non-transparency which this implies, in which the conflicting goals of the organisation are also integrated as well as the coordination requirements within the control room crew and supporting and supervisory roles (i.e. Bainbridge 1983; Craik 1943; Johnson-Laird 1983; Kluwe 1997; Kragt and Landweert 1974; Moray 1996; Vicente et al. 2004; Wilson and Rutherford 1989). Mental models help to inertly visualise performance strategies and their consequences in relation to the organisational goals and explain goal-directed decision making and behaviour. Using their mental models, operators are able to move up and down to different levels of abstraction (Rasmussen 1990; Wickens and Hollands 2000): In the case of a failure of a part or subsystem, the operator thinks at a very concrete level in terms of variables such as steam or water flows, valve settings or heat measurement. At other times, he/she must conceptualise at more abstract levels, for example related to thermodynamics of energy conversion, which requires thinking about the appropriate balance between mass and energy. Finally, the mental model must enable thinking on an even more abstract level, defined in terms of concepts like plant safety, human risk and company profits (Wickens and Hollands 2000). These thoughts will be taken up in Chap. 3 and taken a step further for the derivation of knowledge and skill requirements.

After having described the physical workplace as well as the plants which are usually controlled in process control, in the following, we look at what a control room operator does.

2.2.2 The Operator's Task in Handling Complex Technical Systems: Process Control

As Woods et al. (1987) describe, one of the earliest processes under human control was the making of and tending to fire: "Those responsible for a fire had to add chunks of wood of an acceptable size and condition, at the correct time and in the proper amount, to maintain the fire so that heating and cooking could take place" (Woods et al. 1987, p. 1725). Control of this process was considered to be an art, relying on the operator's skills to sense process conditions directly and to perform appropriate control actions in order to adapt to the requirements. Over time, and affected by industrialisation, processes became larger and products and processes had to meet predefined standards, leading to the introduction of regulators or feedback controllers and a decrease in the direct sensing and experiencing of process states. The human operator has progressed from direct sensing and control of the process (the fires) to the situation in control rooms today, which is characterised by indirect knowledge of the process through instruments fed by sensors and computed measurements and computer control of most elements of the process (Woods et al. 1987).

In Table 2.3., the operator's tasks in process control based on the work of Kragt and Landweert (1974), Woods et al. (1987), Moray (1997, p. 1948), Wickens and Hollands (2000), and Vicente (2007) as well as on our own interviews in continuous process industries (Kluge et al. 2008) are listed and grouped according to the categorisation introduced by Ormerod et al. (1998) for task analysis.

I personally often find it very helpful if one contrasts the activity which one specifically wants to look at with another activity in order to clarify the differences, for example the comparison between the tasks of a control room operator and the tasks upon which industrial and organisational psychology has concentrated over the decades, namely mass production. In **comparison to work in mass production**, control room operators do not work according to a definite work cycle, there is usually no need for physical exertion and no emphasis on speed, meaning that it is inappropriate to apply financial incentive schemes based on piecework measurement because of the continuous flow of production (Crossman 1974). Although the operator's tasks are less physically effortful, occasionally, the mental effort

Table 2.3 The operator's tasks grouped according to sub-goal template method categories

Monitoring
During normal operation, the process must be monitored.
Decision
Disturbances must be detected and their consequences must be predicted.
Any such disturbances must be counteracted.
If faults occur, they must be detected.
Diagnose process problems: the causes of faults must be diagnosed.
Appropriate countermeasures to control the effects of the faults must be selected.
Communication
Read: operating procedures must be consulted as needed.
Receive information/read: databases of information about possible options may need to be consulted.
Record: a record must be kept of significant events.
Give information: significant events must be communicated to other members of the crew and where appropriate to management and maintenance, so that operations may be coordinated and required maintenance operations are undertaken at appropriate times.
Action
Scheduled testing of routine equipment to ensure that backup and safety systems are in an acceptable state.
Changes may be made to the system either during normal or abnormal operations in the light of observations of the system state in order to prevent or compensate for drifts and faults.
Changes may be made manually or by changing the program of automated controllers.
Perform emergency shutdown or other control actions to avoid dangerous accidents, or cooperate with automated system for this purpose.
Combining action and communication
Special actions may be needed during the handover at the end at the shift, or during special conditions such as start-up or shutdown.
Combining monitoring and action
Appropriate strategies must be adopted to support both safety and productivity.
Introduce long-term changes and adjustments to the system so that it will tend to evolve toward a more efficient system.
Combining monitoring, action and communication
After detecting some disturbances or irregularities, operator asks (calls) maintenance worker (on the telephone) to go to a particular component of the plant for a special inspection and to give feedback.
Skill maintenance[a]
Undertake training and retraining to ensure the retention and improvement of skills.
Take a walk through the unit to maintain a "process feel" by directly observing plant components (if applicable, Fig. 2.8).

[a]Skill maintenance is not included by Ormerod et al. (1998) but is listed in several publications

increases during start-ups, shutdowns and breakdowns. Due to the greater distances between workplaces and the remote control, the operator is under less close supervision, for example by the supervisors, but has more direct contact with technical staff and managers, who ask for status information about the plant in order to integrate the activities of many people at many levels of the plant, from management to maintenance workers (Moray 1997). Shift work is common because of the high financial costs of the plant or of waste of material involved if the plant is shut down, for example during the night or at weekends. This also means more responsibility for the operators on night shifts when the engineering staff are less available on site (Crossman 1974).

Digression: Macroergonomics – Task-relevant differences in process industries

The list of tasks for which the operator is responsible includes monitoring and controlling, in terms of action taking. *But what does the operator actually control when "everything is automated"*? In this digression, I would like to describe the particularities of production in the process industry, which in turn provides important hints regarding knowledge and skill acquisition and the subsequent training development, because here, fine differences can be highly relevant to training.

The process industries range from continuous facilities in the petrochemical industry (Fig. 2.9) to large-batch manufacturing in steel production and glass manufacturing, to small-batch manufacturing in the food and pharmaceutical industry (van Donk and Fransoo 2006). Process industries share the characteristic that they handle non-discrete materials (Dennis and Meredith 2000b). "Process industries are businesses that add value to materials by mixing, separating, forming, or chemical reactions. Processes may be either **continuous** or **batch** (bold type added by author) and generally require rigid process control and high capital investment" (Wallace 1984, p. 28). Process industries often initiate their flows with only a few raw materials and subsequently process a variety of blending and resplitting operations, which means that many products are produced from a few kinds of raw material (Fransoo and Rutten 1994, p. 49).

The mixing, separating, forming and chemical reactions are operations that are usually performed on non-discrete products and materials. Commercial chemical processing involves chemical conversions and physical operations and operators also have to operate the process in such a way that the plant is also kept from corroding (Austin 1984), which is why maintenance and servicing plays a very important role in these processes.

These processes can only be performed efficiently using large installation as introduced above, which tend to be an immense investment. If large quantities are demanded, this justifies continuous production. If the demand is low, the investment into a large installation is not worthwhile, and batchwise production is used (Fransoo and Rutten 1994).

Harmful impurities in raw materials must be controlled and product purities monitored (Austin 1984). Material might be forms of gases, liquids, slurries, pulps, crystals, powders, pellets, films, and/or semi-solids which can only be tracked by weight and volume (Dennis and Meredith 2000a). Process industries often obtain their raw materials from mining or agriculture industries (Fransoo and Rutten 1994). These raw materials have natural variations in quality, for example crude oils from different oil fields have different sulphur contents and different proportions of naphtha, distillates, and fuel oils (Figs. 2.10 and 2.11). The production plans and operating schedules need to account for this variability (Dennis and Meredith 2000a). Second, material variability associated with natural raw materials

Fig. 2.9 BP operates the second largest refinery system in Germany (Pictured: cracker plant of the Ruhr oil refinery in Gelsenkirchen, http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/images/presse/raffinerie_verarbeitung/bild_14696.jpg) (retrieved April 8th 2013)

Fig. 2.10 In the aromatics and olefin plant of the Ruhr oil refinery in Gelsenkirchen, e.g. plastic is produced, http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/images/presse/raffinerie_verarbeitung/bild_14690.jpg (retrieved April 8th 2013)

Fig. 2.11 In the distillation plant in the refinery, crude oil is further processed, e.g. into petrol, http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/images/raffinerie_verarbeitung/A8_Destillation_HighRes.jpg (retrieved April 8th 2013)

result in uncertainty about the yield and potency until the process has started, for example in the chemical industry. *Yield* is the fraction of raw material recovered as the main or desired product (e.g. in the synthesis of ammonia, the yield is above approx. 98 %), and *conversion* is the fraction changed into something else, for example by-products or other products (Austin 1984), for instance the conversion of ammonia is limited to about 14 % (per pass), which means that 86 % of the charge does not react and must be recirculated. Conversion is also used to indicate the amount changed by a single pass through a technical subsystem when multiple passes are used (Austin 1984).

The variability in the quality of raw materials might determine which products will be produced (Rice and Norback 1987). Variations in raw material quality, for example moisture content, acidity, colour, viscosity or concentration of active ingredient, can also lead to variations in recipes for producing, for example in

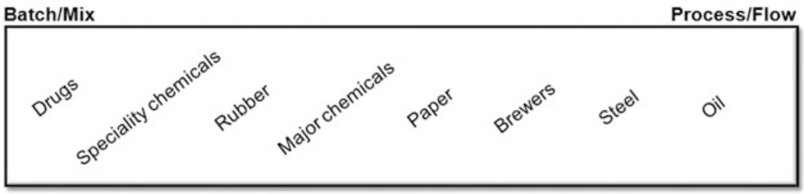

Fig. 2.12 Typology for process industries by Fransoo and Rutten (1994, p. 52)

terms of variations in ingredient proportions required to make quality specifications of the finished product, for instance in the oil or food industries (Fransoo and Rutten 1994, p. 49). Other variations can be caused by variations in quantity and availability or price, for example in the agricultural industry.

To make the difference between continuous and batch processing clear, I refer to the typology introduced by Fransoo and Rutten (1994) and their description of batch/mix and process/flow process industries (Fig. 2.12). Fransoo and Rutten (1994) define **batch/mix** as "*A process business which primarily schedules short production runs of products*" (Fransoo and Rutten 1994, p. 47; Connor 1986).

Process/flow is defined as "*A manufacturer who produces with minimal interruptions in any one production run or between production runs of products which exhibit process characteristics such as liquids, fibres, powders, gases*" (Franso and Rutten 1994, p. 47; Connor 1986).

Batch production can be described as intermittent (Dennis and Meredith 2000b; Woodward 1965), whereas process/flow is continuous or mass production. Batch/mix and process/flow operations can also be combined when the product becomes discrete at some point in the production process (Dennis and Meredith 2000b; Woodward 1965).

In process/flow businesses, the lead time is mainly determined by the cycle time, i.e. the time between two consecutive runs of the same product. The number of different products is limited and there is also a little variety between products. "Little variety, low product complexity and the small number of production steps cause all products to have the same routing" (Fransoo and Rutten 1994, p. 52). Investments in specialised single-purpose equipment are economically justifiable because the total market demand for a relatively small number of products is high. Installations and plants are used continuously around the clock, and material costs account for 60–70 % of the cost price since the production speed is very high (Fransoo and Rutten 1994, p. 52). Control systems for continuous processes aim at minimising fluctuations in process variables caused by different raw materials (e.g. flow rate, composition, temperature) and changes in equipment performance parameters (ASM Consortium 2012), which cannot be handled by the regulatory control system. When an equipment failure occurs, that part of the process often becomes non-functional, which leads to production or product quality loss, potentially resulting in a shutdown of a unit or a plant.

In batch/mix industries, the number of process steps is larger and the level of product complexity is higher (Rippin 1991). In the fine chemical production, sometimes ten different production steps are distinguished. Since the large variety

Table 2.4 Characteristics of process/flow versus batch mix industries (Fransoo and Rutten 1994, p. 53)

Process/flow business	Batch/mix businesses
High production speed, short throughput time	Long lead time, much work in process
Clear determination of capacity, one routine for all products, no volume flexibility	Capacity is not well defined (different configurations, complex routings)
Low product complexity	More complex products
Low added value	High added value
Strong impact of changeover times	Less impact of changeover times
Small number of product steps	Large number of production steps
Limited number of products	Large number of products

of products requires the use of the same, general type of equipment, routings are more diverse. Series of installations are rebuilt and reconnected to make a certain type of process possible (retrofitting), lead times are longer and the work in progress is higher (Fransoo and Rutten 1994). Typically, batch processes are used to manufacture a large number of different products, with a number of grades with minor differences. Frequent product and process changes are constituent characteristic of batch/mix processes, which allow relatively flexible process adjustments (ASM Consortium 2012).

Austin (1984) explains that early chemical processing was usually done in batches and much continues to be done in that way. Only with some exceptions do continuous processes require smaller, less expensive and less material in process than batch processes, and have more uniform operating conditions and products (Austin 1984). Continuous processes require concise control of flows and conditions, in which computer control has proven to be most valuable (Austin 1984). Small quantities of chemicals are usually made by batch/mix processes. When markets enlarge, operations change continuous processing, as the reduction in plant costs per unit of production is often the major force behind the change. In summary, process/flow and batch/mix industries are contrasted in Table 2.4.

End of digression

What is the relevance for skill and knowledge acquisition?

I would like to give a first impression on how these production conditions are relevant for training design. It is very useful for the training designer to at least deal to some extent with the particularities of process control of a respective company in order to understand the particularities of process control. Major differences among process industries exist, such as number of routings, number of raw materials, number of finished goods, equipment type, equipment flexibility, formulation multiplicity, and product variety (Dennis and Meredith 2000b). The following list provides a selection of potentially relevant issues to consider by way of example:

- The forms of production affect the required knowledge about the "recipes" because variation in raw material leads to variations in recipes for producing.

- Operators in batch/mix processes start up plants more frequently and modify them more frequently; operators in process/flow industries do so very rarely, which is relevant in order to decide whether, for example, the start-up of a plant is more of a routine or a non-routine task (see further below).
- Computer control and automation are found much more prominently in process/flow industries, and control operators, for instance in refineries, are more remote from the process they control than, for instance, operators in pharmaceutical production. This has an effect on how disclosed the process is for the operator and consequently also on how abstract the operator needs to conceive the process itself to be.

These reflections are taken up again in Chap. 3 and pursued further for the derivation of the required knowledge and skills.

After introducing the organisational setting from a management and macroergonomics point of view and the observable task, in the following I will translate the description of that which operators do using a terminology which should later allow us, in Chap. 3, to first of all derive requirements from the task description, and arising from this to develop training goals. It stands to reason that the task to handle a complex technical system is in itself equally not simple but complex. However, a complex task is defined through different features than a complex system. In the following, therefore, the constituents of a complex task are introduced.

2.3 Clarifying the Term “Complex Tasks”

When employing the term complex task, I was confronted with the issue of working out the central features of a complex task from the psychological literature of cognitive psychology, cognitive engineering psychology and human factors, because the term complex task is predominantly used without a clear definition. Frequently, the terms complex task and complex skill are also used synonymously (e.g. Lee and Anderson 2001).

2.3.1 Complexity as “Multiple Components”

Unfortunately, a precise definition of a complex task is lacking in the literature. Proctor and Dutta (1995) provide a useful distinction between simple and complex tasks from which to start. Although they do not explicitly define what “simple” and “complex” tasks are actually composed of, their example gives us some useful cues. A simple task, for instance, is to make simple associations between stimuli and responses (Proctor and Dutta 1995), for example to press a specified key in response to the onset of a designated stimulus (Proctor and Dutta 1995, p. 18; Johnson in press). Performing a simple task includes distinguishing between stimuli, integrating stimuli, and naming, comparing, choosing and making simple actions (Bainbridge 1995).

A more complex task, according to Proctor and Dutta's description, is proving geometric theorems, which are made up of multiple components that must be integrated before performance is highly skilled. Complex tasks additionally have perceptual or motor components or depend on background knowledge (Johnson in press). Finally, Proctor and Vu (2006) prescribe that "complex tasks have multiple elements that need to be executed successfully if performance is to be optimal" (p. 276), for example in dual-task performance.

To perform a complex task, the organisation of a sequence of actions is needed (Bainbridge 1995). With regard to process control, sequences of plant activity typically occur in batch processing (see above), during start-up and shutdown and after a fault has been eliminated, and the operator needs to know the general form of the sequence (Bainbridge 1998). The organisation of several sequences is also called multi-tasking (Bainbridge 1995). Multi-tasking requires the interleaving of sequences, especially if a person has several concurrent responsibilities. Loukopoulos et al. (2009) argue that multitasking involves processes in ways that go beyond the requirement of performing each part-task separately.

To organise or integrate several part-tasks into one whole task means choosing between a limited number of options in attempting to perform the part-tasks competing for attention, for example simultaneous execution and interleaving steps of one task with steps of another task (Loukopoulos et al. 2009), which requires tasks to be scheduled appropriately. For the operator it is not enough to know what should be done, but also when it should be done (Kerstholt and Raaijmakers 1997).

The integration of several part-tasks is coordinated by processes of selective attention (devote attention to one task or another, as a notion of attention switch), by divided attention or attention sharing in order to perform, for instance, two tasks simultaneously (Vicente 2007; Wickens and McCarley 2008). To master situations that call for multitasking, operators need a sense of time to enable them to switch between tasks (Rußwinkel et al. 2011). Rußwinkel et al. (2011) as well as de Keyser (1995) assume that task coordination requires a sense of time to cope with the demands of integrating part-tasks into a whole task in terms of timeliness and correctness of actions.

What is the relevance for knowledge and skill acquisition?

In order to provide an initial example and to convey an idea of the extent to which these aspects are relevant for training design, it should be pointed out that ideally, the acquisition of a complex task contains a *process of composition in which multistep procedures are collapsed into a macro procedure* (Lee and Anderson 2001). Additionally, without reaching too far ahead into the chapter on training design to come, according to Wickens and McCarley (2008), for the learning process, it is for example necessary to find the parts of the whole task that can be automated due to their consistency because "these make strong candidates to be uncoupled from full task and submitted to extensive part-task training" (p. 19).

2.3.2 Complexity as Element Interactivity

For this book, which addresses issues of knowledge and skill acquisition in an applied organisational setting for HROs, the definition of a complex task from an instructional perspective by Sweller (2006) is additionally valuable. A complex task defined by Sweller (2006) is characterised by a single construct called "element interactivity". An element is assumed to be everything that needs to be understood or learned (Sweller 2006, p.13), for example the parts and elements of a refinery as well as the chemical processes involved.

To understand the meaning of element interactivity, it is helpful to briefly address mental models here. As briefly introduced above, these are generally used to describe a person's representation of some physical system, and are based on an analog representation of causal relationships and interactions between plant components. Mental models are defined as "mechanisms whereby humans are able to generate descriptions of system purpose and form explanations of a system functioning and observed system states, and prediction of future states" (Rouse and Morris 1985, p. 7; Endsley 2006). As will be explained in Chap. 3, mental models play a fundamental role in controlling complex technical systems (e.g. Kragt and Landweert 1974; Wickens and Hollands 2000), because performance in an organisational context is supposed to be goal-directed (see above "conflicting goals"), for example goals such as production maximisation with the least possible resources needed. Mental models can help to inertly visualise performance strategies and their consequences in relation to the organisational goals. Mental models embody stored long-term knowledge about the system represented, which can be called on to direct applications, for example in non-routine/normal and non-routine/abnormal situations (see below).

When the concern is with acquiring mental models, if elements that need to be understood and learned, for example the process in a refinery unit, interact greatly with each other, they have to be processed and considered simultaneously. Therefore, in cases of high element interactivity, they exceed the limits of the human working memory capacity (Sweller 2006). Working memory holds only the most recently activated, or conscious, portion of long-term memory, and it moves these activated elements in and out of brief, temporary memory storage (Dosher 2003; Sternberg 2009).

The complexity in terms of high element interactivity is *not synonymous with task difficulty*, although it does affect task difficulty. According to Sweller (2006), for instance, for an apprentice in a refinery, learning a large number of chemical elements in the periodic table is probably difficult in the sense that it is effortful, because many elements must be learned. However, it does not contain high element interactivity, elements do not need to be considered simultaneously, and therefore it is not a complex task.

Furthermore, a complex task according to Fisch (2004) needs to be distinguished from a *complicated* task. Playing chess is a complicated task, because one has to learn and apply the rules for each pawn in the game, but it is not considered complex as it is

- not characterised by non-transparency and is in turn considered as transparent (the playing field is visible to everyone, the number of figures is clearly defined, the rules are known by both players in advance),
- not characterised by interconnectivity (the rule on how the knight is allowed to move does not depend on where the queen is or does not change because a pawn has been eliminated) and is
- not characterised by dynamic effects (the chess figures do not move around of their own accord while the player is still thinking about his next move).

What is the relevance for knowledge and skill acquisition?

Element interactivity refers, in the definition by Sweller (2006), not to the task per se, but to the content to be learned. As the complex task of the operator consists of operating a complex system, knowledge is of course also required about the operation of the plant and the process which is being controlled. The understanding of the plant requires the simultaneous processing of interconnected variables because, as described above, interconnectivity constitutes a feature of a complex system and places a strong burden on working memory during learning. In the acquisition of knowledge, it is therefore important to consider that such instructional techniques are selected that optimally support rather than overtax working memory during the processing of learning information.

2.3.3 A Definition of a Complex Task for This Book

Looking at the manifold occupations in HROs, it becomes clear that there is no such thing as "the" complex task. One complex task, such as process control, can be quite different from another complex task, such as piloting.

What we can say overall as a commonality of different applications of complex tasks, that which is a generalised lowest common denominator, *is that a complex task is composed of various part-tasks*. This does not emerge explicitly from the precise definition of a complex task, but rather implicitly from the descriptions above as well as from training approaches examined to date, in which a distinction was drawn between part-task and whole-task training (e.g. Patrick 1992). One assumes that a complex task (as a whole task) can be broken down into parts, for example by means of a task decomposition (Frederiksen and White 1989).

A part-task frequently consists of several steps or *sequences*. Mostly, the part-tasks are performed *in parallel* and have to be *integrated* into a joint flow of action. A *coordination of the part-tasks* ensues through attention selection, attention switching, and attention sharing (Wickens and McCarley 2008). Finally, in HROs, which form the focus of this book, workers performing complex tasks are working in teams and also have to coordinate and orchestrate their individual tasks

Table 2.5 Characteristics of a complex task

Characteristics
A complex task consists of part-tasks
Part-tasks include sequences of steps
Part-tasks have to be integrated
Part-task integration requires coordination based on attentional processes
Coordination requires simultaneous processing of interacting knowledge elements in order to reach a predefined goal
An individual complex task needs to be orchestrated into an interdependent team task

into an *interdependent team task* (Roth and Woods 1988) as outlined in the section on Collaborative complex problem solving (Sect. 4.4.1) in non-routine/abnormal situations. The characteristics of a complex task are listed in Table 2.5.

In summary, *a complex task can be decomposed into part-tasks that include sequences of steps, which need to be integrated and coordinated based on attentional processes and need to be orchestrated based on the simultaneous processing of knowledge elements (mental model) into a interdependent team task to meet the organisational goals.*

In the following chapter, the concern is with the situational conditions under which the control room operator performs his or her tasks. These situational conditions, the routine, non-routine/normal and non-routine/abnormal situations still belong on the one hand to organisational and task analysis (see Preface), but equally provide indications of which conditions need to be considered for transfer, which are in turn important for the derivation of training objectives and evaluation criteria.

2.4 Conditions for Knowledge and Skill Application: Routine, Non-routine/normal and Non-routine/abnormal Situations

In this book, I will distinguish between routine and non-routine as well as between non-routine/normal and non-routine/abnormal situations, in which in the latter case it is no longer possible to continue operating a plant using normal procedures (Fig. 2.13). Although widely used, the terms routine, non-routine, normal and abnormal are not well defined in the human factors and ergonomics publications.

Based on the often used distinction between the two poles of routine and nonroutine/abnormal situations, process control tasks are characterised as “hours of intolerable boredom punctuated by a few minutes of pure hell” (Wickens and Hollands 2000, p. 517), or “99 % boredom and 1 % sheer terror” (Vicente et al. 2004, p. 362).

The “hours of intolerable boredom” (although a little overstated) are seen as the times in which the human operator is monitoring a plant that is automatically controlled. This is the routine situation, routine control and regulation of the process which is well handled by Standard Operating Procedures (SOPs). The “pure hell” refers to the task of timely detection, diagnosis, and corrective action in situations in

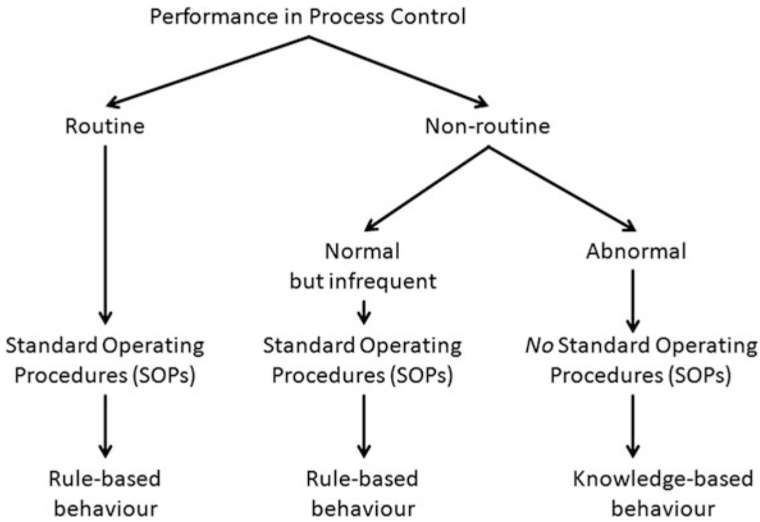

Fig. 2.13 Overview of the conditions of performance, own illustration

which infrequent malfunctions occur that can be fixed by using SOPs (non-routine/ normal) or for which operators have no procedures at hand (non-routine/abnormal).

In terms of deriving strategies for learning and instruction later on, it is relevant to distinguish **routine** from **non-routine** tasks as well as **normal** from **abnormal** situations as the conditions under which the operator has to perform his/her tasks (Fig. 2.13).

Conditions for knowledge and skill application in routine situations

Routine situations as defined by Wickens and Hollands (2000) require normal control and regulation of the process which is well handled by Standard Operating Procedures (SOPs). Normal situations include tasks such as process monitoring, or scheduled testing of routine equipment. Routine tasks are rule-based behaviour (Rasmussen and Jensen 1974; Rasmussen 1990). Most of the time, routine situations occur, in which the automation works well and the process is well handled by the operator through SOPs. The main task is to monitor system instruments and periodically adjust control settings to maintain production quantities within certain boundaries (Reinartz 1993; Wickens and Hollands 2000).

In this book, routine stands for a property of the task, in the sense of frequency with which it is performed. Routine therefore stands for the number of repetitions per day, week or year. Moreover, routine stands for a defined, unchanging process. Additionally, from an organisational point of view, Ahuja and Carley (1999) define the degree of routineness as a function of the extent to which the task contains no or low variety (Perrow 1967), a small number of exceptions over time (Daft and Macintosh 1981) and therefore represent predictability and sameness (Ahuja and Carley 1999). Organisational routines in terms of SOPs develop in response to recurring questions (Gersick and Hackman 1990).

Condition for knowledge and skill application in non-routine/normal situations

Non-routine tasks are infrequent, for example the start-up and shutdown of the plant or a unit before and after a revision. But also for non-routine but infrequent tasks, standard procedures exist and can still be considered as normal (Reinartz 1993). In this book, I define non-routine/normal situations as situations in which operators encounter, for example, a malfunction of the automation and have to draw on skills and procedures which have not been used for a longer period of time. In line with Wickens and Hollands (2000), non-routine tasks might be fairly standardised and can be handled by following a set of procedures (SOPs), for example the start-up or shutdown of a plant is called non-routine, since shutdowns and start-ups occur rarely. Non-routine/normal situations also encompass rule-based behaviour (Rasmussen and Jensen 1974; Rasmussen 1990). SOPs are designed to support operators to store and process information correctly in the correct order (Kluge et al. 2013). SOPs include sequences of actions which need to be performed in a fixed sequence of actions or in parallel or dependent (contingent) on specific decision points (see Chap. 2).

Due to the infrequent occurrence, these might be carried out with less automaticity (Reinartz 1993; Schneider 1999). This means that non-routine tasks are less robust to distraction and need more attentional resources accompanied by conscious control and high mental workload, with less reserve capacity (Vidulich 2003), for example for coping with stress, compared to tasks performed with high automaticity. Additionally, these non-routine situations frequently require a so-called “first-shot” performance (Hammerton 1967, p. 63), in which the concern is with initial performance after a retention interval or a period of non-use. There is no second chance or a second attempt. It has to be as close to perfect as possible at the first attempt (Patrick 1992, p.78).

And finally, also from an organisational and economic perspective, for example in the petrochemical industries, non-routine situations are of interest because they cost 3–8 % of capacity, which amounts to approx. 10 billion $ annually in lost production (Bullemer and Laberge 2010, p. 10)

Condition for knowledge and skill application in non-routine/abnormal situations

In an *abnormal* situation, a disturbance or series of disturbances in a process cause plant operations to deviate from their normal operating state. They include “unfamiliar sequences of unplanned and unexpected sequences and either not visible or not immediately comprehensible” (Perrow 1984, p. 78), as introduced above to explain effects of interconnectivity and coupling. The nature of the abnormal situation may be of minimal or catastrophic consequence. It is the job of the operator or the control room crew to identify the cause of the situation and execute compensatory or corrective actions in a timely and efficient manner. Abnormal situations extend, develop, and change over time in the dynamic process control environments, increasing the interconnectivity of the intervention requirements (ASM® Consortium, Abnormal Situation Management Consortium 2012).

Non-routine/abnormal situations include, for example, a fault or situation that has never occurred before and there is a need for problem solving (an extreme example is the case of the tsunami that swept over the NPP of Fukushima). In such cases, knowledge-based behaviour is required (Rasmussen and Jensen 1974; Rasmussen 1990), which expresses itself in complex problem solving (Funke and Frensch 2007; Fischer et al. 2012; Reinartz 1993) and dynamic decision making (Brehmer 1992). An abnormal situation is considered to be a problem because the human operator has several goals (see definition of "multiple goals" above) but does not know how these goals can be reached. If the operator cannot go from the given situation to the desired situation simply by predefined actions (e.g. SOPs), "there has to be a recourse to thinking" (Duncker 1945, p. 1; Fischer et al 2012). Based on the work by Brehmer (1992) and Edwards (1962), dynamic decision making (DDM) "has been characterized by multiple, interdependent, and real-time decisions, occurring in an environment that changes independently as a function of a sequence of actions" (Gonzales et al. 2003, p. 591).

In this book, abnormal situations are what Stachowski et al. (2009, p. 1536) and Gladstein and Reilly (1985), in line with Hermann (1963), define as a "crisis situation", which is (a) *ambiguous* and includes (b) *unanticipated* major (c) *threats* to system survival coupled with (d) *limited time* to respond (Hermann 1963). Non-routine/abnormal tasks are less predictable and require creativity (Ahuja and Carley 1999). Abnormal situations "are *low-probability*, *high-impact* events that threaten the reliability and accountability of organizations and are characterized by ambiguity of cause, effect, and means of resolution" (Yu et al. 2008, p. 452 based on Pearson and Clair 1998). They are unusual, out-of-the-ordinary, or atypical (Weinger and Slagle 2002, p. 59). Ambiguity is correlated with uncertainty, incomplete and noisy information (Vicente et al. 2004). Grote (2009) distinguishes between several types of uncertainty, such as:

- Source of uncertainty: Incomplete information, inadequate understanding, undifferentiated alternatives
- Content of uncertainty: State uncertainty, effect uncertainty, response uncertainty
- Lack of control: Lack of transparency, lack of predictability and lack of influence.

The main problem in this respect is that in case of the situation in which the system state is uncertain (Vicente et al. 2004), it is unclear which SOPs there even are, and if there is no SOP, which actions lead to a suitable solution.

Looking at the disasters and accidents of the past few years, such as the "Deepwater Horizon" in 2010 and Fukushima 2011, it becomes clear that such non-routine/abnormal situations contain these aforementioned uncertainties, which can also occur simultaneously. A dramatic example of the requirement is provided by the disaster management in Fukushima in 2011. The plant personnel had to handle the situation with "loss of all the safety systems, loss of practically all the instrumentation, necessity to cope with simultaneous severe accidents on four plants, lack of human resources, lack of equipment, lack of light in the installations, and general conditions of the installation after the tsunami and after damage of the fuel resulted in hydrogen explosions and high levels of radiation" (IAEA Report 2011, p. 43).

Table 2.6 Summary and delimitation of the terms routine, non-routine/normal and non-routine/abnormal situation

Conditions for transfer	Description
Routine situations	Require routine control and regulation of the process
	Based on rule-based behaviour
	The situation is well handled by Standard Operating Procedures (SOPs)
	e.g. "daily business", plant monitoring and control
Non-routine/normal situations	Require drawing on skills which have not been used for a longer period of time,
	Rule-based behaviour
	The situation is well handled by Standard Operating Procedures (SOPs)
	e.g. "exceptional business", fault repair or start-up of plant, but is still rule-based behaviour
Non-routine/abnormal situations	Require problem-solving skills and knowledge-based behaviour
	Situation is (a) *ambiguous* and includes (b) *unanticipated* major (c) *threats* to system survival coupled with (d) *limited time* to respond
	e.g. low-probability, high-impact situation, an explosion in a subunit of the plant caused by a safety-related rule violation or natural disasters such as earthquakes, tsunami.

In Table 2.6, the transfer conditions are concisely summarised.

Although the transitions between routine, non-routine/normal and non-routine/abnormal are not discrete but continuous, the artificially clear-cut distinction is assumed to be helpful in order to better understand and design knowledge and skill acquisition processes, as will be explained in the following chapters.

Delimitation of the human factors perspective from the plant operations perspective on normal and abnormal situations

The distinction between routine, non-routine/normal and non-routine/abnormal situations is a psychological one. From a learning and training psychological perspective, the distinction between routine and non-routine reflects the frequency of opportunities to use a skill (Ford et al. 1992), i.e. the skill is routine and performed with a minimal use of cognitive and attentional resources. Opportunity to perform is the extent to which a trainee is provided with or actively obtains work experiences relevant to the tasks for which he/she was trained (Ford et al. 1992, p. 512). From that perspective, non-routine and routine tasks are distinguished according to the number of times trained tasks have been applied (Ford et al. 1992), so that a certain level of task experience has been achieved (Tesluk and Jacobs 1998). The longer the period of non-use is because of a lack of opportunity to perform, the more skill decay will occur (Arthur et al 1998; Kluge et al. 2012). If the work environment (e.g. due to high automated processes keeping the human operator not "in the loop") offers no opportunity to perform – also not artificially in immersive environments or with low-cost alternatives such as symbolic rehearsal (Driskell et al. 1994; Kluge et al. 2012) – the lack of opportunity to perform and apply trained skills is a strong negative predictor of the skill retention

Table 2.7 Operational modes and critical systems perspective defined by the ASM (Bullemer and Laberge 2010)

Operational modes	Plant states	Critical systems	Operational goals	Plant activities
Emergency	Disaster	Area emergency response system	Minimise impact	Fire fighting
	Accident	Site emergency response system		First aid rescue
Abnormal	Out of control	Physical and mechanical containment system Safety shutdown Protective systems Hardwired emergency alarms	Bring to safe state	Evacuation
	Abnormal	DCS alarm system Decision support system Process equipment	Return to normal	Manual control & troubleshooting
Normal	Normal	DCS, automatic controls Plant management systems	Keep normal	Preventative monitoring & testing

DCS distributed control system

and performance level (Bjork and Bjork 2006; Burke and Hutchins 2007; Farr 1987).

The distinction between normal and abnormal is equally a psychological one and refers not to the plant state (as in the ASM or IAEA definition in Tables 2.7 and 2.8), but rather to the familiarity to the human operator. It refers to whether a task has, in principle, already been trained and executed and for which there is an SOP which one could use (= normal), which requires a so-called temporal transfer, or whether there was no training for this task and also no SOPs (= abnormal), which then requires an adaptive transfer (Kluge et al 2010).

From a continuous flow operations perspective (e.g. of refineries and petrochemical plants), the distinction between normal and abnormal is a different one and in terms of plant states, critical systems, operational goals and plant activities as displayed in Table 2.7.

The consequences of abnormal situations, for example in a chemical plant, depend on the nature of the materials, for example hazardous vs. non-hazardous chemicals, solids, liquids or gases; flammable vs. non-flammable substance being processed (ASM Consortium 2012). The definition in Nuclear Safety is different (IAEA 2007) and deviates from the ASM Definition. The IAEA (2007) distinguishes between "Operational states" and "Accident conditions" (Table 2.8).

Normal operation in NPP is defined as operation within specified operational limits and conditions, which includes start-up, power operation, shutting down, maintenance, testing and refuelling. Accident conditions are defined as deviations from normal operation that are more severe than anticipated operational occurrences, including design basis accidents and severe accidents, for example major fuel failure or loss of coolant accident. Accident Management includes prevention of escalation of the event into a severe accident, mitigation of consequences of a

Table 2.8 Plant states defined by the IAEA (2007) for NPP

Plant states		Characteristics
Operational states		*Normal operation*
		Operation within specified operational limits and conditions (includes startup, power operation, shutting down, maintenance, testing and refuelling)
		Anticipated operational occurrences[a]
		Operational process deviates from normal operations, which is expected to occur at least once during the operating lifetime of a facility, but which in view of appropriate design provision does not cause any significant damage to items important to safety or lead to accident conditions (e.g. loss of normal electrical power, faults such as turbine trip, malfunction of individual items of a normally running plant, failure of function of single items of control equipment, loss of power to main coolant pump)
Accident conditions	Within design basis accidents	*Design basis accidents* (is designed against a facility and for which the damage to the fuel and the release of radioactive material are kept within authorised limits)
		Not design basis accidents, but encompassed by them
	Beyond design basis accidents...	*Severe accidents* (more severe than design basis accidents)
		...Without severe accidents

[a]Some organisations use the term *abnormal* situation instead of anticipated operational occurrences (IAEA 2007, p. 145)

severe accident and achieving a long-term safe and stable state, and is defined as the taking of actions during the evolution of a beyond design basis accident (IAEA 2007, p. 145).

In summary, this means that the terms routine, non-routine, normal and abnormal from the human factors and the operations perspective are also differently viewed and defined according to the respective branch. In this book, the starting point is the consideration of required knowledge and skills, and situations and conditions under which they need to be applied.

To give some examples and an outlook on the coming chapters, it is important that as a training designer, one is, or becomes, one is aware of what routine, non-routine/normal, and non-routine/abnormal situations are for the organisation for which the training is conceived. Which SOPs exist? Which processes are rather frequent, and which rather rare? In batch/mix processes, the start-up, for instance, is more routine than in continuous/flow industries. Which tasks are performed every day, every week, or only once a year or once every 10 years? And what serious consequences can arise if a procedure is not correctly mastered?

Answers to these questions and the distinction between routine, non-routine/normal and non-routine/abnormal are important, for example, in order to later conduct a so-called DIF analysis (Difficulty-Frequency-Importance analysis, Buckley and Caple 2007), which, in turn, is important in order to define training method, duration or repetition (see Chaps. 4 and 5).

Moreover, from the distinction between routine, non-routine/normal and non-routine/abnormal, it can be derived under which mental workload conditions an operator has to perform his/her task. Waller et al. (2004) assume routine tasks to be moderate-workload and non-routine to be high-workload situations. Additionally, I assume non-routine/abnormal situations to be situations with high mental workload under stress. Therefore, additionally, the answers to the question of what non-routine/normal and non-routine/abnormal situations are need to be used to consider particular training methods such as stress exposure training (Driskell and Johnston 1998; Driskell et al. 2008, see Chaps. 4 and 5).

In addition to the cognitive aspects of dealing with abnormal situations on a knowledge-based level as introduced above, the handling of abnormal situations requires coping with high stress. The purpose of Stress Exposure Training based on Driskell et al. (1998, 2001, 2008) is to provide the operator with the skills and tools necessary to maintain effective performance when operating in high-stress situations (Salas et al. 2006). This training is especially important when the consequences of errors are high, as stress increases the likelihood of errors.

After "setting the scene" by introducing and describing complex technical systems, the task, duties and responsibilities of operators and operator crews and conditions under which performance has to be shown, in Chap. 3, I go into detail regarding the aspects which I have so far only touched on by way of example, by deriving knowledge and skills that need to be acquired for performing complex tasks in routine, non-routine/normal and non-routine/abnormal situations.

References

Ahuja, M. K., & Carley, K. M. (1999). Network structure in virtual organizations. *Organization Science, 10*, 741–757.

Arthur, W., Bennett, W., Stanush, P. L., & McNelly, T. L. (1998). Factors that influence skill decay and retention: A quantitative review and analysis. *Human Performance, 11*, 57–101.

ASM Consortium. (2012). *Process factors*. Retrieved November 12, 2012. http://www.asmconsortium.net/defined/sources/Pages/ProcessFactors.aspx

Austin, G. T. (1984). *Shreve's chemical process industries* (5th ed.). New York: McGraw-Hill.

Bainbridge, L. (1983). Ironies of automation. Increasing levels of automation can increase, rather than decrease, the problems of supporting the human operator. *Automatica, 19*, 775–779.

Bainbridge, L. (1995). *Processes underlying human performance: Complex tasks*. Retrieved September 7, 2012. http://www.bainbrdg.demon.co.uk/Papers/EmbrRid/EmbrRidB.html

Bainbridge, L. (1998). *Planning the training of a complex skill*. Retrieved January 11, 2012. http://www.bainbrdg.demon.co.uk/Papers/PlanTrain.html

Bjork, R. A., & Bjork, E. L. (2006). Optimizing treatment and instruction: Implications of the new theory of disuse. In L. G. Nilsson & N. Ohta (Eds.), *Memory and society. Psychological perspectives* (pp. 109–134). Hove, UK: Psychology Press.

Blech, C., & Funke, J. (2005). *DYNAMIS review: An overview about applications of the DYNAMIS approach in cognitive psychology* (Research Report). Heidelberg: Department of Psychology, University of Heidelberg.

Brehmer, B. (1992). Dynamic decision making: Human control of complex systems. *Acta Psychologica, 81*, 211–241.

Brehmer, B., & Dörner, D. (1993). Experiments with computer-simulated microworlds: Escaping both the narrow straits of the laboratory and the deep blue sea of the field study. *Computers in Human Behavior, 9*, 171–184.

Buckley, R., & Caple, J. (1990/revised 5th edition 2007). *The theory and practice of training*. London: Kogan Page.

Bullemer, P., & Laberge, J. (2010, November 30). *Abnormal situation management and the human side of process safety*. Paper presented at the ERTC 15th annual meeting, Istanbul, Turkey. Retrieved November 12, 2012. http://www.asmconsortium.net/Documents/HumanSideofSafety_ERTC%20Forum_Bullemer_30Nov10.pdf

Bullemer, P. T., Cochran, T., Harp, S., & Miller, C. (1997). Managing abnormal situations II: Collaborative decision support for operations personnel. *ASM Consortium*. Retrieved November 11, 2012. http://www.asmconsortium.net/Documents/Managing%20ASM%20Dec%20Support.pdf

Burke, L. A., & Hutchins, H. M. (2007). Training transfer: An integrative literature review. *Human Resource Development Review, 6*, 263–296.

Carvallo, P. V. R., dos Santos, I. L., & Vidal, M. C. R. (2005). Nuclear power plant shift supervisors' decision making during microincidents. *International Journal of Industrial Ergonomics, 35*, 619–644.

Connor, S. J. (1986). *The process industry thesaurus*. Falls Church: American Production and Inventory Control Society.

Craik, K. (1943). *The nature of explanation*. Cambridge: University Press.

Crossman, E. R. F. W. (1974). Automation and skill. In E. Edwards & F. P. Lees (Eds.), *The human operator in process control* (pp. 1–25). London: Taylor & Francis.

Daft, R. M., & Macintosh, N. (1981). A tentative exploration into the amount and equivocality of information processing in organizational work units. *Administrative Science Quarterly, 26*, 207–224.

De Keyser, V. (1995). Time in ergonomics research. *Ergonomics, 38*, 1639–1661.

Dennis, D. R., & Meredith, J. R. (2000a). An analysis of process industry production and inventory management systems. *Journal of Operations Management, 18*, 683–699.

Dennis, D. R., & Meredith, J. R. (2000b). An empirical analysis of process industry transformation systems. *Management Science, 46*, 1085–1099.

Dörner, D. (1989/2003). *Die Logik des Misslingens. Strategisches Denken in komplexen Situationen* [The logic of failure. Strategic thinking in complex situations] (11th ed.). Reinbeck: rororo.

Dosher, B. A. (2003). Working memory. In L. Nadel (Ed.), *Encyclopedia of cognitive science* (pp. 569–577). London: Nature Publishing Group.

Driskell, J. E., & Johnston, J. H. (1998). Stress exposure training. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress. Implications for individual and team training* (pp. 191–217). Washington, DC: APA (Reprinted in 2006).

Driskell, J. E., Copper, C., & Moran, A. (1994). Does mental practice enhance performance? *Journal of Applied Psychology, 79*, 481–492.

Driskell, J. E., Johnston, J. H., & Salas, E. (2001). Does stress training generalize to novel situations? *Human Factors, 43*, 99–110.

Driskell, J. E., Salas, E., Johnston, J. H., & Wollert, T. N. (2008). Stress exposure training: An event-based approach. In P. A. Hancock & J. L. Szalma (Eds.), *Performance under stress* (pp. 271–286). Aldershot: Ashgate.

Duncker, K. (1945). The structure and dynamics of problem-solving processes. *Psychological Monographs, 58*(5), 1–112.

Edwards, W. (1962). Dynamic decision theory and probabilistic information processing. *Human Factors: The Journal of the Human Factors and Ergonomics, 4*, 59–74. doi:10.1177/001872086200400201.

Emery, F. E. (1959). *Characteristics of socio-technical systems* (Tavistock Documents # 527), London. Abridged in F. E. Emery, *The emergence of a new paradigm of work*. Canberra: Center for Continuing Education.

Endsley, M. R. (2006). Expertise and situation awareness. In K. A. Ericsson, N. Charness, P. J. Feltovich, & R. R. Hoffmann (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 633–652). Cambridge: Cambridge University Press.

Farr, M. J. (1987). *The long-term retention of knowledge and skills. A cognitive and instructional perspective*. New York: Springer.

Fisch, R. (2004). Was tun? – Hinweise zum praktischen Umgang mit komplexen Aufgaben und Entscheidungen (Titel des Kapitels auf S. 319)/Was tun angesichts komplexer Aufgaben (Titel im Inhaltsverzeichnis, S. 6) [What to do? Guidelines for the practical management of complex tasks and decisions]. In R. Fisch & D. Beck (Hrsg./Eds.), *Komplexitätsmanagement. Methoden zum Umgang mit komplexen Aufgabenstellungen in Wirtschaft, Regierung und Verwaltung* (pp. 319–345). Wiesbaden: VS Verlag für Sozialwissenschaften.

Fischer, A., Greiff, S., & Funke, J. (2012). The process of solving complex problems. *The Journal of Problem Solving, 4*, 19–42.

Ford, J. K., Quinones, M. A., Sego, D. J., & Speer -Sorra, J. (1992). Factors affecting the opportunity to perform trained tasks on the job. *Personnel Psychology, 45*, 511–527.

Fransoo, J. C., & Rutten, W. G. M. M. (1994). A typology of production control situations in process industries. *International Journal of Operations and Production Management, 18*, 47–57.

Frederiksen, J. R., & White, B. Y. (1989). An approach to training based upon principled task decomposition. *Acta Psychologica, 71*, 89–146.

Funke, J. (1985). Steuerung dynamischer Systeme durch Aufbau und Anwendung subjektiver Kausalmodelle [Control of dynamic systems via construction and application of subjective causal models]. *Zeitschrift für Psychologie, 193*, 443–465.

Funke, J. (2010). Complex problem solving: A case for complex cognition? *Cognitive Processing, 11*, 133–142.

Funke, J., & Frensch, P. A. (2007). *Complex problem solving: The European perspective-10 years after* (pp. 25–47). Mahwah: Lawrence Erlbaum Associates.

Gaddy, C. D., & Wachtel, J. A. (1992). Team skills training in nuclear power plant operations. In R. W. Swezey & E. Salas (Eds.), *Teams: Their training and performance* (pp. 379–396). Norwood: Alex.

Gersick, C. J., & Hackman, R. (1990). Habitual routines in task performing groups. *Organizational Behavior and Human Decision Process, 47*, 65–97.

Gladstein, D. L., & Reilly, N. P. (1985). Group decision making under threat: The Tycoon game. *Academy of Management Journal, 28*, 613–627.

Gonzales, C., Lerch, J. F., & Lebiere, C. (2003). Instance-based learning in dynamic decision making. *Cognitive Science, 27*, 591–635.

Grauel, B., Kluge, A., & Adolph, L. (2012). *Analyse vorausgehender Bedingungen für die Unterstützung makrokognitiver Prozesse in Teams in der industriellen Instandhaltung*. Paper presented at the 2nd workshop "Kognitive Systeme", Universität Duisburg-Essen, 18–20 September 2012.

Grote, G. (2009). *Management of uncertainty. Theory and application in the design of systems and organizations*. Dordrecht: Springer.

Hagemann, V., Kluge, A., & Ritzmann, S. (2012). Flexibility under complexity: Work contexts, task profiles and team processes of high responsibility teams. *Employee Relations, 34*, 322–338.

Hammerton, M. (1967). Measures for the efficiency of simulators as training devices. *Ergonomics, 10*, 63–65.

Hansez, I., & Chmiel, N. (2010). Safety behavior: Job demands, job resources, and perceived management commitment to safety. *Journal of Occupational Health Psychology, 15*, 267–278.

Hermann, C. F. (1963). Some consequences of crisis which limit the viability of organizations. *Administrative Science Quarterly, 8*, 61–82.

Hollnagel, E., & Woods, D. D. (2005). *Joint cognitive systems. Foundations of cognitive systems engineering*. Boca Raton: Taylor & Francis.

IAEA. (2007). *IAEA safety glossary. Terminology used in nuclear safety and radiation protection* (2007 edn). Retrieved November 13, 2012. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1290_web.pdf

IAEA. (2011). IAEA international fact finding expert mission of the Fukushima Dai-ichi NPP accident following the great east Japan earthquake and tsunami. Report to the IAEA member states. Retrieved December 3, 2012, from http://www-pub.iaea.org/mtcd/meetings/pdfplus/2011/cn200/documentation/cn200_-final-fukushima-mission_report.pdf

Johnson, A. (in press). Procedural memory and skill acquisition. In A. F. Healy & R. W. Proctor (Vol. Eds.), & I. B. Weiner (Ed.-in-Chief), *Handbook of psychology: Vol. 4. Experimental psychology* (2nd edn). Hoboken: Wiley.

Johnson-Laird, P. N. (1983). *Mental models. Towards a cognitive science of language, inference, and consciousness*. Cambridge: Cambridge University Press.

Kerstholt, J. H., & Raaijmakers, J. G. W. (1997). Decision making in dynamic task environments. In R. Ranyard, W. R. Crozier, & O. Svenson (Eds.), *Decision making. Cognitive models and explanations* (pp. 205–217). London: Routledge.

Kim, J. H., & Seong, P. H. (2009). Human factors engineering in large-scale digital control systems. In H. P. Seong (Ed.), *Reliability and risk issues in large scale safety-critical digital control systems* (Springer series in reliability engineering, III, pp. 163–195). London: Springer. doi:10.1007/978-1-84800-384-2_8.

Kluge, A., Schüler, K., & Burkolter, D. (2008). Simulatortrainings für Prozesskontrolltätigkeiten am Beispiel von Raffinerien: Psychologische Trainingsprinzipien in der Praxis. *Zeitschrift für Arbeitswissenschaft, 62*(2), 97–109.

Kluge, A., Sauer, J., Burkolter, D., & Ritzmann, S. (2010). Designing training for temporal and adaptive transfer: A comparative evaluation of three training methods for process control tasks. *Journal of Educational Computing Research, 43*, 327–353.

Kluge, A., Burkolter, D., & Frank, B. (2012). "Being prepared for the infrequent": A comparative study of two refresher training approaches and their effects on temporal and adaptive transfer in a process control task. In *Proceedings of the Human Factors and Ergonomics Society 56th annual conference* (pp. 2437–2441), Boston. Thousand Oaks: SAGE.

Kluge, A., Grauel, B., & Burkolter, D. (2013). Job aids: How does the quality of a procedural aid alone and combined with a decision aid affect motivation and performance in process control? *Applied Ergonomics, 44*, 285–296.

Kluwe, R. H. (1997). Acquisition of knowledge in the control of a simulated technical system. *Le Travail Human, 60*, 61–85.

Kragt, H., & Landweert, J. A. (1974). Mental skills in process control. In E. Edwards & F. P. Lees (Eds.), *The human operator in process control* (pp. 135–145). London: Taylor & Francis.

Lee, F. J., & Anderson, J. R. (2001). Does learning a complex task have to be complex? A study in learning decomposition. *Cognitive Psychology, 42*, 267–316.

Loukopoulos, L. D., Dismukes, R. K., & Barshi, I. (2009). *The multitasking myth. Handling complexity in real-world operations*. Farnham: Ashgate.

Moray, N. (1987). Intelligent aids, mental models, and the theory of machines. *International Journal of Man-Machine Studies, 27*(5), 619–629.

Moray, N. (1996, October). A taxonomy and theory of mental models. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 40*(4), 164–168. Sage.
Moray, N. (1997). Human factors in process control. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (pp. 1944–1971). New York: Wiley.
Ormerod, T. C., Richardson, J., & Shepherd, A. (1998). Enhancing the usability of a task analysis method: A notation and environment for requirements specification. *Ergonomics, 41*(11), 1642–1663.
Patrick, J. (1992). *Training: Research and practice*. San Diego: Academic.
Pearson, C. M., & Clair, J. A. (1998). Reframing crisis management. *Academy of Management Review, 23*, 59–76.
Perrow, C. (1967). A framework for the comparative analysis of organizations. *American Sociological Review, 32*, 194–208.
Perrow, C. (1984). *Normal accidents: Living with high risk technology*. New York: Basic Books (Reprint 1999, by Princeton University Press, Princeton).
Proctor, R. W., & Dutta, A. (1995). *Skill acquisition and human performance*. Thousand Oaks: Sage.
Proctor, R. W., & van Zandt, T. (2008). *Human factors in simple and complex systems* (2nd ed.). Boca Raton: CRC Press.
Proctor, R. W., & Vu, K.-P. L. (2006/reprint 2009). Laboratory studies of training, skill acquisition, and retention. In K. A. Ericsson, N. Charness, P. J. Feltovich, & R. R. Hoffman (Eds.), *The Cambridge handbook of expertise and expert performance* (pp. 265–286). Cambridge: Cambridge University Press.
Rasmussen, J. (1990). Mental models and the control of action in complex environments. In D. Ackermann & M. J. Tauber (Eds.), *Mental models and human computer-interaction 1* (pp. 41–69). Amsterdam: North-Holland.
Rasmussen, J., & Jensen, A. (1974). Mental procedures in real-life tasks: A case study of electronic troubleshooting. *Ergonomics, 17*, 293–307.
Reason, J. (2008). *The human contribution. Unsafe acts, accidents, and heroic recoveries*. Surrey: Ashgate.
Reinartz, S. J. (1993). An empirical study of team behaviour in a complex and dynamic problem-solving context: A discussion of methodological and analytical aspects. *Ergonomics, 36*, 1281–1290.
Reinartz, S. J., & Reinartz, G. (1992). Verbal communication in collective control of simulated nuclear power plant incidents. *Reliability Engineering and System Safety, 36*, 245–251.
Rice, J. W., & Norback, J. P. (1987). Process industries production planning using matrix data structures. *Production and Inventory Management Journal, 28*, 15–23.
Rippin, D. W. T. (1991). Batch process planning. *Chemical Engineering, 98*, 100–107.
Roth, E. M., & Woods, D. D. (1988). Aiding human performance I: Cognitive analysis. *Le Travail Humain, 51*, 39–64.
Rouse, W. B., & Morris, N. M. (1985). *On looking into the black box: Prospects and limits in the search for mental models* (No. DTIC#AD-A159080). Atlanta: Center for Man-Machine system Research, Georgia Institute of Technology.
Rußwinkel, N., Urbas, L., & Thüring, M. (2011). Predicting temporal errors in complex task environments: A computational and experimental approach. *Cognitive Systems Research, 12*, 336–354.
Salas, E., Wilson, K. A., Priest, A., & Guthrie, J. W. (2006). Design, delivery, and evaluation of training systems. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (pp. 472–512). Hoboken: Wiley.
Schneider, W. (1999). Automaticity. In R. A. Wilson & F. C. Keil (Eds.), *The MIT encyclopedia of the cognitive science* (pp. 63–64). Cambridge, MA: MIT Press.
Stachowski, A. A., Kaplan, S. A., & Waller, M. J. (2009). The benefits of flexible team interaction during crisis. *Journal of Applied Psychology, 94*, 1536–1543.

Sterman, J. D. (1994). Learning in and about complex systems. *System Dynamics Review, 10*, 291–330.

Sternberg, R. J. (2009). *Cognitive psychology*. Wadsworth: Cengage Learning.

Sweller, J. (2006). How the human cognitive system deals with complexity. In J. Elen & R. E. Clark (Eds.), *Handling complexity in learning environments. Theory and research* (pp. 13–27). Amsterdam: Elsevier.

Tesluk, P. E., & Jacobs, R. R. (1998). Toward an integrated model of work experience. *Personnel Psychology, 51*, 321–355.

Van Donk, D. P., & Fransoo, J. C. (2006). Operations management research in process industries. *Journal of Operations Management, 24*, 211–214.

Veland, O., & Eikas, M. (2007). A novel design for an ultra-large screen display for industrial process control. In M. J. Dainoff (Ed.), *Ergonomics and health aspects. HCII 2007* (LNCS 4566, pp. 349–358). Berlin: Springer.

Verschuur, W., Hudson, P., & Parker, D. (1996). *Violations of rules and procedures: Results of item analysis and test of the behavioural model. Field study NAM and shell expro Aberdeen*. Leiden: Report Leiden University of SIP.

Vicente, K. J. (2007). Monitoring a nuclear power plant. In F. Kramer, D. A. Wiegmann, & A. Kirlik (Eds.), *Attention. From theory to practice* (pp. 90–99). Oxford: Oxford University Press.

Vicente, K. J., Mumaw, R. J., & Roth, E. M. (2004). Operator monitoring in a complex dynamic work environment: A qualitative cognitive model based on field observations. *Theoretical Issues in Ergonomic Science, 5*, 359–384.

Vidulich, M. A. (2003). Mental workload and situation awareness. Essential concepts in aviation psychology. In P. S. Tsang & M. A. Vidulich (Eds.), *Principles and practice of aviation psychology* (pp. 115–147). Mahwah: Lawrence Erlbaum.

Walker, G. H., Stanton, N. A., Salmon, P. M., Jenkins, D. P., & Rafferty, L. (2010). Translating the concepts of complexity to the field of ergonomics. *Ergonomics, 53*, 1175–1186.

Wallace, T. F. (1984). *APICS dictionary* (5th ed.). Falls Church: American Production and Inventory Control Society.

Waller, M. J., Gupta, N., & Giambatista, R. C. (2004). Effects of adaptive behaviors and shared mental models on control crew performance. *Management Science, 50*, 1534–1544.

Weinger, M. B., & Slagle, J. (2002). Human factors research in anesthesia patient safety: Techniques to elucidate factors affecting clinical task performance and decision making. *Journal of the American Medical Informatics Association, 9*, 58–63.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River: Prentice Hall.

Wickens, C. D., & McCarley, J. S. (2008). *Applied attention theory*. Boca Raton: CRC Press.

Wilson, J. R., & Rutherford, A. (1989). Mental models: Theory and application in human factors. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 31*(6), 617–634.

Woods, D. D. (1984). Visual momentum: A concept to improve the cognitive coupling of person and computer. *International Journal of Man-Machine Studies, 21*, 229–244.

Woods, D. D., O'Brien, J. F., & Hanes, L. F. (1987). Human factors challenges in process control: The case of nuclear power plants. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 1725–1770). New York: Wiles.

Woods, D. D., Roth, E. M., Stubler, W. F., & Mumaw, R. J. (1990). Navigating through large display networks in dynamic control applications. In *Proceedings of the Human Factors and Ergonomics 34th annual meeting* (pp. 396–399). doi:10.1177/154193129003400435.

Woodward, J. (1965). *Industrial organization: Theory and practice*. London: Oxford University Press.

Yu, T., Sengul, M., & Lester, R. H. (2008). Misery loves company: The spread of negative impacts resulting from organizational crisis. *Academy of Management Review, 33*, 452–472.

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