A HUMAN FACTORS APPROACH TO THE OPTIMISATION OF STAFFING IN THE PROCESS INDUSTRY

Joanne Stokes,[1] Karl Rich,[2] and Tony Foord [3]

[1] Senior Human Factors Consultant, Human Engineering Limited, Shore House, 68 Westbury Hill, Westbury-on-Trym, Bristol BS9 3AA.

[2] Associate Director, Human Engineering Limited, Shore House, 68 Westbury Hill, Westbury-on-Trym, Bristol BS9 3AA.

[3] Principal Engineer, 4-sight Consulting, Southern Office, 51 Cowper Road, Harpenden, AL5 5NJ.

SYNOPSIS

Staffing arrangements for process plant have been studied extensively in recent years taking account of the many interdependent variables influencing system performance (individual competence, equipment, teamwork and communications, procedures and organisation). This paper describes work to determine the optimum staffing using human engineering tools such as task analysis, function allocation, workload analysis, and human reliability analysis.

INTRODUCTION

For several decades, staff rationalisation has been driven by a wide range of factors. Advances in technology, organisation, education and training have enabled significant increases in productivity. As a result of best practice, major incidents and regulatory pressure, facility operators have also strived to reduce exposure to major hazards.

This has left the industry with highly automated plant and processes that in many instances have been “over-alarmed”, and a residual workforce obliged to multi-task and take ownership for secondary and tertiary activities. In some instances this has led to exposure to high workload, fragmented jobs and risk that has been displaced rather than eliminated.

Some companies are responding to this by adopting a user-centred, risk-based approach to staffing. This requires the participative rationalisation of processes and their associated alarms and procedures and a better allocation of function between operators and equipment. This can lead to an improvement in, and better prioritisation of, task allocation.

This can be achieved by developing a better understanding of the target audience and utilising this knowledge through task analysis and allocation of function. The baseline data can then be subjected to workload and human reliability analysis (to a level appropriate for the perceived risk). This allows the definition of roles, and appropriate and coherent job design. From this, training which is targeted, cost-effective and matches the requirement can be developed.

The Health and Safety Executive Contract Research Report “Assessing the safety of staffing arrangements for process operations in the chemical and allied industries” [HSE CRR 348, 2001] and the “Best Practice Guide” [Energy Institute, 2004] provide techniques for checking whether a particular staffing is sufficient to meet the requirements for safety. The [HSE CRR 348, 2001] report states “It is not designed to calculate the minimum or optimum number of staff.” and also states about other human factors techniques for assessing staffing:
“it is concluded that many of the techniques are research tools, requiring specialist skills to interpret even though they may be straightforward to apply. A method tailored to assessing staffing arrangements, and designed for general use, has not been produced.”

This paper describes an approach that still requires the use of human factors specialists, but is suitable for general use to determine the optimum workload and the optimum staffing.

BACKGROUND

For several decades, improvements in technology, organisation, education and training have enabled significant increases in productivity, often described as reductions in workload, staff rationalisation or reduction in staffing. For example, before 1995 a gas processing unit had 40 staff, mainly on shifts. Following a review this was reduced to 25 staff in 1996. Subsequent experience meant that the numbers were increased by one or two, but the number of staff is still well below 30. Another unit had a large design team in a building close to a compressor processing large volumes of natural gas at high pressure. The design team was moved off-site and the number of people exposed to the hazards from the compressor house reduced to two staff making brief inspections once a shift. Examples of the improvements that have enabled this type of reduction are:

- Improved materials that last longer reducing maintenance
- Evolution of process technology, for example small hydro-cyclones replacing cumbersome separators
- High speed telecoms enabling remote operation
- Increased scale of facilities producing more output per operator
- Better education and training resulting in multi-skilled operators
- More automation reducing manual tasks

Initiatives like these have been adopted by industry for a number of reasons such as increasing safety and production, minimising negative environmental effects, and reducing the number of staff exposed to major hazards.

However, the impact of these changes on the remaining workforce is not always well defined or understood. Problems can arise during and after the changes have been implemented for example, existing staff can become overworked or may not be competent to undertake their new roles. This could result in staff making errors, cutting corners, or taking unacceptable risks. Since the introduction of Control Of Major Accident Hazards (COMAH) [HSE web-site, 2005] in 1999, the understanding of human factors within industry has grown, but is still not yet well defined or applied.

Particular concerns with reduced staffing are:

- That staff may be able to manage normal operation, but the number may not be sufficient for abnormal or emergency operation; and
- Not all changes reduce workload.

For example, many processes have been upgraded by replacing the control systems with a modern system. Unfortunately the ease with which alarms may be configured on modern computer control systems has resulted in many operators being presented with alarms at an unreasonably high frequency from the “improved” system. Other systems have been designed using telecoms to enable remote operation, even when the facility is off-shore. Operators and maintenance technicians then find the “improved” design requires daily visits to the unmanned site involving significant travel by car or even helicopter. Not only is the workload increased but the risks to staff are significantly increased because of all the additional travel.

The issues with alarms are already well documented by the Engineering Equipment and Materials Users Association [EEMUA, 1999]. The issues with assessing whether staff may be able to manage abnormal or emergency operation are much more difficult. The workload is not fixed and depends upon how the staff are educated, trained and organised. Thus key questions are what is the optimum automation, workload and organisation and what is the optimum staffing to handle it?

OUTLINE OF USER-CENTRED APPROACH

This paper describes a user-centred approach which tackles these key questions. The approach uses established human factors methods, which when integrated into the design of a new system, or into a change management plan, can ensure that the workload and staffing requirements are fully understood and optimised for that system. This helps to reduce the risk of staff-related incidents and to contribute to safer systems. Specifically, this approach can optimise the staffing by:

- Appropriately distributing responsibilities across roles;
- Predicting and managing the workload experienced by each role; and
- Identifying and controlling or mitigating the risks associated with the change.

The output from this assessment can also be used to define:

- Job role specifications;
- The competencies, skills, and knowledge required to perform these duties;

- A suitable organisational structure providing adequate supervision and support;
- Communication and user requirements;
- Training and continued performance requirements;
- Ergonomic designs and layout for equipment; and
- A change management plan.

This human factors approach can also be used to provide a key input into the safety case for COMAH [HSE web-site, 2005].

Figure 1 presents the overall human factors approach discussed in this paper.

UNDERSTANDING THE TASK REQUIREMENTS

Understanding how the system operates is the first step in defining the optimal number staff in any system; that is, to identify every activity that is required to operate and maintain that system in all conditions (for example, normal, abnormal and upset). This provides an overall picture of the task requirements for that system. The process by which this can be achieved is called task analysis.

TASK ANALYSIS

Task analysis takes the existing (and, where appropriate, predicted) tasks and produces a model of the activities necessary to operate and maintain the system. This model can take a variety of forms for example, through hierarchical, cognitive, or tabular task analyses. An extract of a theoretical tabular task analysis for a generic process plant is presented in figure 2.

The task analysis forms the baseline data upon which to allocate roles and responsibilities. The generation of this data should therefore be discussed and validated by key stakeholders (including current staff) to ensure that it represents an accurate picture of the activities required for that system.

As Figure 2 illustrates, the data collected does not have to be merely lists of tasks, but can also answer a large range of questions, including:

- What initiated the task?
- Who is responsible for the task?
- What information is required by staff to complete the task?
- What system is used to achieve the task?
- How is it achieved?
- What is the output?
- What verbal communication is required?

This user-centred approach ensures that the task analysis represents those activities that actually take place, rather than merely summarising operating or maintenance procedures for how it *should* be done. This approach is beneficial as it incorporates 'on the job' or tacit knowledge into the task analysis, minimising the potential for this knowledge to be lost over time or when staff change jobs. This approach also facilitates identification of possible gaps or issues with current working practices. For instance, in the following example:

> Two foremen unnecessarily placed themselves at risk by entering a cloud of propylene vapour in an attempt to isolate a leak. Fortunately the vapour did not ignite. Upon complaining that that he should not have been expected to place himself under such risk, he recalled that remotely located emergency equipment had been put in 8 years earlier, after a similar incident. Although the operation of this equipment was carried out once a week by one of the operators, neither foreman had been in contact with these valves during this time, and had long since forgotten that they were there.

A task analysis of the plant area could have identified:

- Who was responsible for the safety of the plant area;
- Who operated / checked on the safety valve;

- What information was required by staff in the event of this type of incident occurring;
- What communication links existed between staff on site (for example, foreman and operator);
- What plant safety procedures and / or briefings exist for that plant area;
- What safety procedures and working practices were in place.

The task analysis would have highlighted the missing communications link between the foreman and the operator. Moreover, asking staff to verbalise and consider their roles during the development of the tasks analysis may also have brought these issues to light.

ALLOCATION OF FUNCTION

A critical part of understanding staffing requirements is to identify which of the activities identified in the task analysis should be assigned to which part of the system. This can be achieved through allocation of function. Allocation of function is the identification of activities undertaken by the staff, those that can be performed automatically by the system, and those that require interaction between the staff and the system. During this time, any proposed changes to the system (for example, automation, remote support, reallocation of tasks, etc), need to be considered.

Allocating tasks to either the staff or the system should be determined by the nature of that task. For example, the characteristics of humans place certain limitations on the types of task that they can be expected to perform safely and reliably. The following represents Fitts' list [Fitts, 1968], a definition of the types of tasks best suited to humans and / or machines.

Humans may surpass machines in their ability to:

- Detect small amounts of visual or acoustic energy.
- Perceive patterns of light or sound.
- Improvise and use flexible procedures.
- Store very large amounts of information for long periods and to recall relevant facts at the appropriate time.
- Reason inductively.
- Exercise judgement.

Whereas machines currently surpass humans with regard to the ability to:

- Respond quickly to control signals, and to apply great force smoothly and precisely.
- Perform repetitive, routine tasks.
- Store information briefly and then to erase it completely.
- Reason deductively, including computational ability.
- Handle complex operations; that is, to do many different things at once.

However, as technology has advanced the ability of humans to exceed machines for some activities has reduced. For example, machines are now able to employ pattern recognition techniques that can rival and often surpass the human eye.

Therefore, it is important to also consider the *context* within which the activities are taking place in order to maximise the abilities of both humans and machines in that context; rather than relying on a set of predefined and somewhat rigid parameters. [Sherry and Ritter, 2002] have provided the following guidance for defining appropriate human / machine allocation:

- **Minimise the impact of interruptions on the operator** (to reduce the risk of mistakes being made, especially when performing critical tasks);
- **The human should be an active participant rather than a passive monitor** (active operators minimise the risks of reduced vigilance, complacency, loss of skills / situational awareness);
- **Humans have responsibility and must be given control authority** (operators provided with sufficient information / mechanisms are better disposed to safely and effectively evaluate and control the system);
- **The automation should clearly indicate its behaviour and state** (clear information ensures that the operator can maintain awareness and understanding the current system status);
- **The automation must be capable of inferring the human and environment context and state** (system awareness can facilitate communication, coordination and development of a shared understanding).

It is also important to consider other sites and industries that use similar systems. For example, lessons can be learned from their existing system configurations, working practices and any incident reports / databases.

ESTABLISHING BASELINE DATA

Once tasks have been systematically labelled as ‘human’ tasks, the responsibilities associated with those tasks can be logically allocated into the proposed staff roles. For example, this could be achieved by separating responsibilities according to plant processes or areas, or levels of responsibility. These staff roles form the baseline data upon which to demonstrate that the system can feasibly be operated safely and efficiently by the proposed staffing. As illustrated in Figure 1, this is achieved by assessing the workload placed upon each proposed role, and by identification, control, and mitigation of operator-related risks associated with this structure, through workload analysis and through targeted human reliability analysis.

FEASIBILITY AND PERFORMANCE

WORKLOAD ANALYSIS

Workload Analysis provides assurance that staff are capable of performing all necessary tasks associated with their job role in normal (including start-up, shut-down and maintenance), abnormal, and upset conditions, without being subjected to periods of unacceptably high or low workload. This analysis is beneficial in establishing the appropriate staffing for the system; it also verifies the appropriate allocation of functions between systems and operators, and can be used to assess the human-machine interface in terms of the stresses and demands it places upon the workforce.

The type of workload assessment carried out depends on the project requirements. For example, a qualitative assessment could be carried out relatively inexpensively, and is particularly beneficial in the early design stages of a system, and can also be compared with user assessments carried out when testing mock-ups of the final system. A qualitative assessment may be carried out by a human factors specialist, supported by the stakeholders, to assess the predicted operating conditions of a system and identify periods of high, medium and low workload.

A quantitative analysis can, however, provide a more in-depth analysis. For example, a quantitative assessment requires the specialist to explore operations at the task level, identifying the type of task an operator carries out (visual, auditory, cognitive or psychomotor). The specialist then interrogates a number of developed scenarios to determine whether the operator would be required to perform two ‘competing’ tasks (that is, respond to two visual stimuli, or perform two cognitive tasks) simultaneously. The success of a quantitative workload assessment depends upon the level of detail held within the task analysis.

Identifying an acceptable workload over all working conditions indicates that the operator should be able to perform the tasks required to operate / maintain that system. However, any peaks or troughs of workload identified indicate that the operator may have difficulty in completing those activities.

> For example, a workload analysis was carried out in a control room on a Floating Production, Storage and Offloading (FPSO) vessel. The operator was observed to experience up to 15,000 alarms in a 12-hour shift period that equal to approximately 1 alarm every 3 seconds (assuming, at best, an equal distribution of alarms). This number of alarms is obviously too many for one operator to contend with in such a short space of time.
>
> In the FPSO example above it was recommended that the alarms interface be rationalised to remove any obsolete or redundant alarms, using the alarms guidance defined in [EEMUA, 1999], and that a post-implementation workload analysis be carried out to ensure that the adverse workload caused by the alarms had been controlled.
>
> Another example is a gas storage facility that conducted a large scale alarm rationalisation study, based upon [EMMUA, 1999], removing a number of obsolete, duplicate, and information only alarms from their Distributed Control System (DCS). During this process it was identified that an operator could

> receive a large number of alarms all relating to the same event, e.g. a compressor trip. In cases such as this, alarms were grouped together, resulting in an initial high priority alarm to notify the operator, suppressing the remaining alarms for a defined period of time. Thus the number of alarms presented to the operator had been reduced, with those remaining optimised.

These examples illustrate how the amount of information presented to staff can be reduced. However, the amount of workload experienced by the operator is not simply a function of the number of alarms presented. Although alarms rationalisation does reduce the number of unnecessary alarms presented to the operator, it also increases the requirement for the operator to respond to each alarm; as each remaining alarm now requires a response.

Where adverse workloads have been identified, it is important to understand which activities may pose a significant problem. A screening process can be applied to those tasks, to identify which tasks have potentially serious consequences in terms of the environment, production or safety. For these critical tasks, functions and features of the system may require redesign in order to limit their capacity to cause human error. Redesign may involve allocating functions to the system rather than the operator (in the event of cognitive overload) or modifying the interface or timing of events. It may also require that the job roles and responsibilities are re-specified; staff numbers are increased (where workload has been identified as too high) or decreased (where staff are underloaded) accordingly.

Some companies have reduced the exposure to major hazards (e.g. on off-shore installations) by introducing remotely-located experts. These experts perform a number of different activities from full DCS monitoring to analysing trend data to providing ad-hoc advice as required. Outsourcing some of the responsibilities associated with operating the installation obviously reduces the number of staff required off-shore. However, problems can arise when remotely located staff have not visited the installation and do not have a vital visual representation of the installation. Furthermore, this is compounded by the fact that they do not have the same physical perceptions as a locally located operator e.g. they are not able to 'see' the plant outside or feel the impact of a storm. Different working practices and safety assurances must be introduced, and the ability to communicate with the field operators on the installation becomes of paramount importance.

> Remotely-located experts to provide immediate contextual advice on abnormal situations were used on a trial basis on an off-shore installation. The use of effective communication media (including real-time video) to transmit information was identified as a critical influence on the success of the project.

Sufficient consideration has not always been given to which responsibilities and communication mechanisms would be most appropriate and how these remote activities might fit into the current systems of work. Reorganisation of responsibilities of staff is a natural by-product of most system and organisational changes. These changes usually affect the competencies required from the staff and need to be systematically analysed in order to reduce operating costs safely.

> In the 1990s a contract organisation were supporting 6 to 8 offshore platforms using technicians for planned maintenance. They had the opportunity to take on additional platforms through a change of ownership so that they then supported 14 offshore platforms in total. As a result of a Criticality Analysis the maintenance strategy was changed, and they were able to take on the extra work with only a small increase in staff. In summary, they doubled the number of assets they maintained with only a 10% increase in staff.

Iteration of the workload analysis can therefore determine whether the re-designs have resulted in appropriate workloads. Where it is not possible to 'design out' the potential for human error, critical activities can be subject to a human reliability analysis to identify, control and / or mitigate the potential for human error to ensure that the system as a whole is safer.

HUMAN RELIABILITY ANALYSIS (HRA)

The use of Human Factors works on the premise that staff are part of the system. As part of the system individuals are affected by previous, current and future tasks that they have or would have to perform. They are also be affected by other factors that are outside the control of system (fatigue, personal factors, etc). A human reliability analysis is aimed at understanding human performance, and creating a system that accommodates these characteristics to achieve a safer system.

There are number of formal human reliability analysis methods however, the overall methodology for the identification and mitigation of operator-related errors is very similar. As outlined in Figure 1, HRA is a four stepped process, aimed at answering the following questions:

1. What human errors are possible?
2. What is the likelihood of them occurring and what are the chances of recovery?
3. What are the potential consequences of each error occurring?
4. How can human errors be controlled or mitigated?

To determine the potential for human error during each critical activity, a realistic and detailed scenario needs to be produced. This scenario should describe in detail the tasks required to safely maintain plant operations during normal, abnormal and upset conditions. In this manner the potential for operator-related risks associated with performing plant operations under all operating conditions are examined.

> For example, it is more likely that an operator would make an operational error when under time pressure, such as handling a gas flare incident, than when the operator is monitoring plant operations in a steady state.

Once an exhaustive list of errors has been identified for each task, the likelihood of each error occurring can be determined; the risk to the environment, production and safety can be defined; and the potential to recover from the error ascertained. This process is usually undertaken in collaboration with stakeholders who have experience of the system (operators, other staff, etc) as their knowledge in the generation and assessment of errors can be invaluable.

The following presents an example output from a HRA as it may have been used to define the potential, likelihood and consequences of human error relating to the ‘propylene vapour leak’ detailed earlier.

- **Role**: Foreman
- **Critical task**: Isolating the propylene vapour leak.
- **Direct Risk**: Foreman does not communicate knowledge of the leak to the control room operator and is not aware of the safety procedure to isolate the leak (*external error*).
- **Description**: The Foreman and the operator do not communicate sufficiently even though the operator has an overview of the plant and has the ability to isolate the leak remotely.
- **Consequence**: The Foreman tackles the leak at the source and suffers severe burns.
- **Risk rating**: Medium
- **Potential mitigation measures**:
  - Mandate regular familiarisation of plant specific operating and safety procedures;
  - Update safety procedures to mandate informing operator of problem (where appropriate);
  - Conduct regular safety drills;
  - Provide short and long-term plant training and awareness programmes;
  - Increase formal (weekly) communication between staff.

It is not always practical nor rationale to apply reduction measures to all of the errors identified during the HRA. In some instances the cost of implementing the measure would far out weigh the benefits. Therefore, implementation of risk reduction measures is usually based upon a cost - benefit analysis whereby those high impact / poor likelihood of recovery errors are subjected to appropriate control or mitigation strategies to reduce their occurrence to As Low As Reasonable Practicable (ALARP).

Once the control or mitigation measures have been identified they should be incorporated into the project risk register and into the system design. Where strategies have been identified, it is beneficial to re-assess the potential for errors to ensure that the risk has been removed or is ALARP. This can involve reiteration of the workload analysis under the revised configuration to ensure that the workload now falls within an acceptable range. Iteration of the human reliability analysis should also be performed as necessary.

STAFFING OPTIMISATION

This human factors approach provides the basis upon which operators can provide assurance that the human element of the system has been systematically and rigorously analysed in system design and in the change management process. It can also demonstrate that the staffing identified is optimised to ensure safe and efficient system operations.

This approach also provides a key human factors input into the safety case for COMAH by demonstrating that the operator has:

- Understood how humans, as well engineering fallibility, can initiate accidents;
- Identified all system critical tasks and activities;
- Systematically analysed the system to ensure that staff can safely conduct plant operations by:
    - Avoiding adverse workload;
    - Identifying, analysing and mitigating the potential for human errors;
    - Defining appropriate staffing;
    - Identifying an organisational structure with appropriate management and supervisory capabilities;
- Identified initial training needs;
- Provided competency assurance;
- Encouraged employee involvement and communication;
- Sufficient information to inform:
    - Ergonomically sound workplace design and layouts;
    - Short-term and long-term training and performance requirements;
    - On-going data collection, risk assessment and support.

REFERENCES

1. **HSE web-site** - *Control of Major Accident Hazards Regulations*, (1999) Definition and guidance can be found at http://www.hse.gov.uk/comah/index.htm. Website last accessed 1st October 2005.

2. **HSE CRR348, 2001**, *Assessing the safety of staffing arrangements for process operations in the chemical and allied industries.*

3. **Energy Institute, 2004,** *IP Safe staffing arrangements - user guide for CRR348/2001 methodology and its extension to automated plant and/or equipment*, ISBN 0 85293 411 4.

4. **Fitts, P.M., 1962,** Functions of man in complex systems. *Aerospace Engineering*. 21 January. Describes a list of human attributes and limitations and specifies those tasks more suitable for a machine.

5. **Richard R. Sherry and Frank E. Ritter, 2002,** *Dynamic Task Allocation: Issues for Implementing Adaptive Intelligent Automation.* School of Information Sciences and Technology. The Pennsylvania State University. Technical Report No. ACS 2002-2. 8 July 2002.

6. **EEMUA (Engineering Equipment and Materials Users Association), 1999,** *Alarms systems. A guide to design, management and procurement*. Publication No. 191.

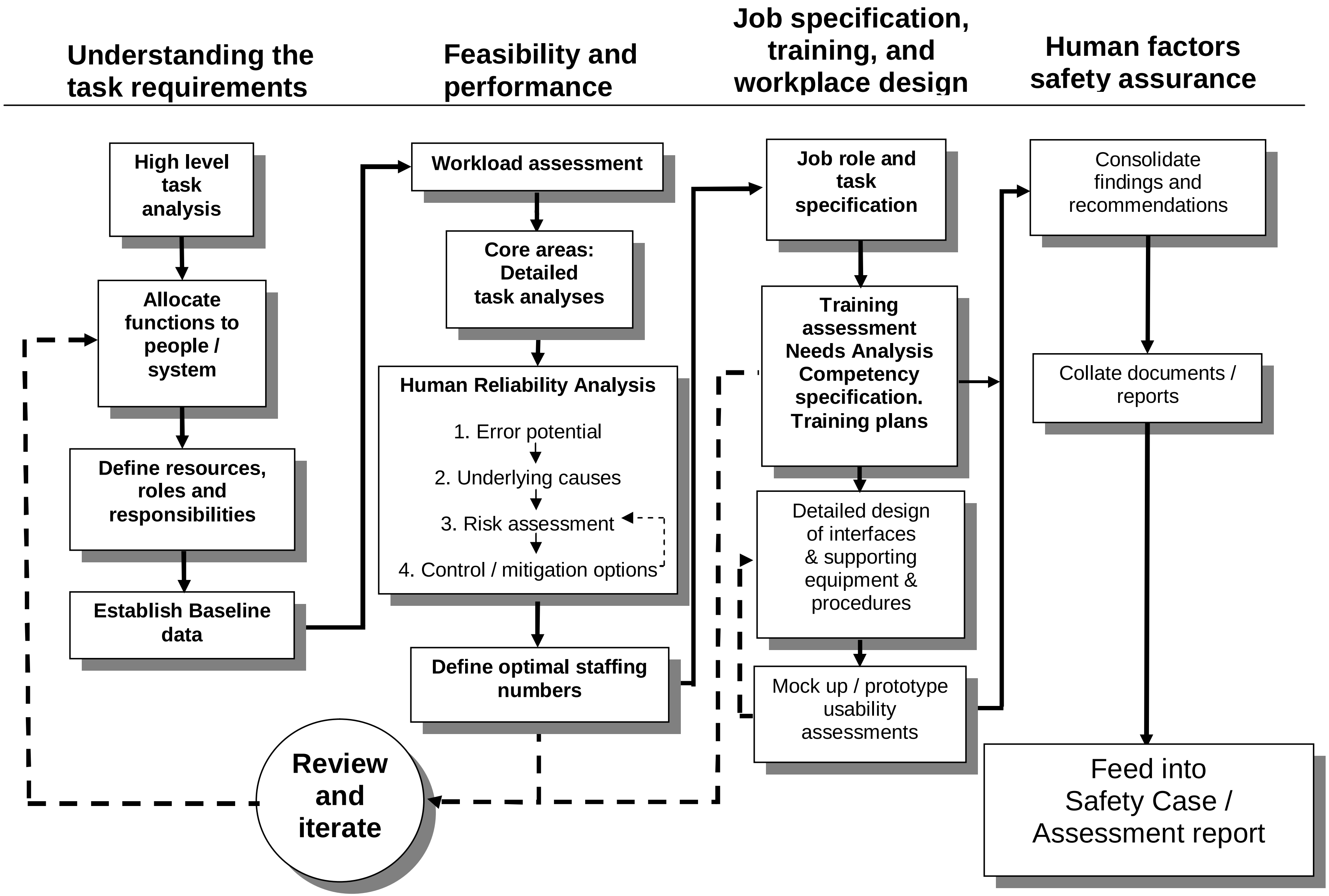

Figure 1 – Human Factors Approach

Task number	Task	Task Initiator	Role Responsible	Information Required	System	Transaction	Output	Communications	Plan
2.1	Hear/see plant alarm	The audible and visual alert on the DCS	Control room technician	DCS and its function in the MCR	DCS	Operator hears and sees the alarm on the DCS	Alarm visually located	n/a	
2.2	Interpret alarm (identify meaning of alarm)	Knowledge that the alarm refers to a valve tripping	Control room technician	DCS, knowledge of plant area	DCS	Operator identifies the meaning and prority of the alarm	Alarm is identified	n/a	
2.3	Accept alarm by pressing button on DCS console and/or the mimic	To inform the system that the CRT has detected the alarm	Control room technician	DCS, knowledge of the system interface, knowledge of alarm procedures	DCS	Operator acknowledges alarm	Alarm is acknowledge d	n/a	
2.4	Decide on appropriate response to alarm	Knowledge that the valve should not have tripped	Control room technician	Knowledge of the plant operation, knowledge of the valve	N/A	Decision is made over how best to respond to the alarm	Decision is made over how best to respond to door breach	n/a	If corrective action on DCS go to 2.5, if field operator to investigate go to 2.6, else return to 1
2.5	Take corrective action using DCS	Further investigation on the DCS is required	Control room technician	Knowledge of DCS, knowledge of normal operating set-points for valve	DCS	Appropriate action is to be taken on the DCS	Action is taken on the DCS		
2.6	Instruct FO by radio to investigate and/or take action	Further investigation by a field operator is required	Control room technician	Knowledge of radio operation, knowledge of problem	Radio	Information to be relayed to the FO	FO is furnished with details of the problem	Control Room Technician - Field operator	
2.7	Verify that corrective action has been successful via feedback from radio communications with FO	The success of the action is not known	Control room technician	Knowledge of: radio operation, the problem, the action taken to recover	Radio	Feedback on the success of the action to be relayed back to the CRT	CRT receives feedback on success of the action	Field operator - Control Room Technician	If corrective action is successful goto 1, if it is not successful goto 2.8

Figure 2 – Extract from a generic process plant tabular task analysis