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Ergonomics in control room design

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Ergonomic contributions in early design phases of large-scale projects are not yet common practice. In this paper a description is given of a control room design project, in which ergonomists participated from the very beginning. First, the scope of the project and a methodical approach to the design are introduced. This is followed by an overview of the activities of ergonomists in this particular project. The second part of this paper concerns the experiences with this methodical approach and design practice. These are discussed by the former control room project manager, one of the ergonomists, the interior architect and a user representative. It is concluded that it is possible to include ergonomics as well as user participation in every design phase without getting behind on time schedules and keeping within available budgets. A lot of useful design and engineering data could be derived from the situation analysis in the existing situation and the full-scale mock-up evaluation that was carried out. Besides workplace design, job design (operator workload) and work organization design were essential to the success of the project.

1. Introduction

Designing control rooms for large-scale process industries is, as a rule, a complicated matter. In practice, during detailed engineering attention is given to ergonomic aspects such as the outfitting of a work station and environmental factors. An ergonomic contribution to the earlier design phases is not yet common practice.

In 1980 a project was started to extend the ESSO Refinery in Rotterdam by adding new process units to upgrade the set of final products produced ('whitening the barrel'). The project included many new process units and a major revamp of the existing refinery. The total investment was about US $1 billion. In 1986 the project was completed by the successful start-up of the ESSO FLEXICOKER Refinery.

Full control of all process units was essential to realize the profits on which this large investment had been justified. It was obvious to the refinery management that special attention should be paid to the design of the control room.

Esso Refinery decided to consult ergonomists of the Twente University Ergonomics Group from the very start of the project, knowing that their approach is oriented towards the tasks of the control centre and how these were (or could be) performed. Ergonomists had been involved with this company prior to this in reorganizing the

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layout and facilities of an existing control room for product storage and product loading (Verhagen 1980).

Although the ergonomists had to meet design deadlines, they were allowed time for the analysis of the existing control room, preparing mock-up sessions and to elaborate work organizational issues. Finally, in 1988 an evaluation of the control room as built was carried out in the consolidated control centre (CCC). In short, the ergonomists had an opportunity to carry out their job in the way it should be carried out in a more or less ideal situation. The authors would like to share their experiences with others since there is a strong need for evidence of the usefulness of a substantial ergonomic contribution in design projects.

2. Ergonomic system design

If one is to realize the input of ergonomists and users in design projects a methodical approach is a necessity. The approach to system design used in this project was presented in the contribution by Pikaar *et al.* (1990). The essential steps comprising this approach are described below.

2.1. *Structuring the design problem*

First, the outline of the design steps and the extent and type of user participation are negotiated with project management.

2.2. *Situation analysis*

The situation analysis is a combination of a formal specificiation of the user(s)–machine(s)–system (UMS) and a task analysis of the existing situation. In addition, a study on the future use of the UMS must be carried out, taking into account the system boundaries, the general design criteria and the design constraints.

2.3. *Allocation of system tasks*

An allocation of system tasks is explicitly carried out to determine the number and type of tasks to be performed by human operators and the automated part of the system.

2.4. *User participation*

Experienced process operators can offer valuable contributions to the design of control rooms and work stations. The operators can provide wide and detailed process knowledge and practical experience that is not documented or known to designers or process staff.

3. Structuring ergonomic issues into the design project

After several meetings of the project owner (ESSO Refinery management) and the ergonomists a number of agreements were drafted and scheduled. First, a control room project team was formed in which the following functions and disciplines were represented: the owner, instrumentation and computer specialists, ergonomists and the process section head. For communication between project team and operators, a reference committee was set up. The reference committee consisted of two operators per shift (five shifts), two shift supervisors and two members of the on-site process staff (see figure 1). The operators acted as liaison between their shift and the project team. The committee held meetings regularly, which were partly devoted to ergonomic aspects. A day-supervisor became a member of the control room project team and worked closely with the ergonomists.

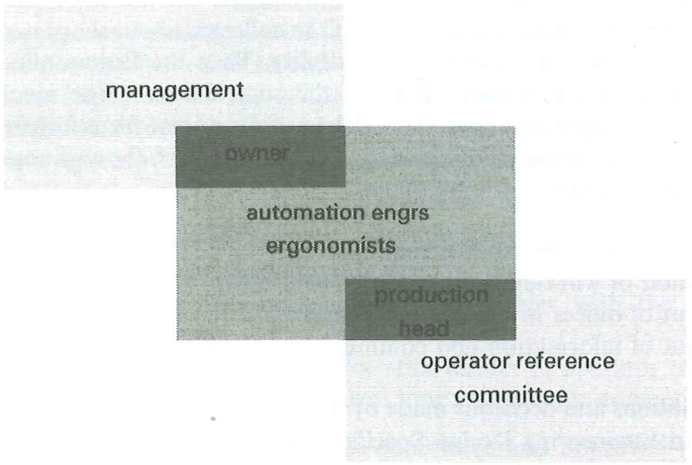

Figure 1. Project organization.

Next, the activities of the ergonomists were scheduled in line with Exxon design procedures; Exxon Research and Engineering (USA) agreed to include the ergonomics contributions to the project.

There are three design phases

(1) *Design Basis*: this sets the basis of the project. What do we want to achieve and in what way? For example, if reliability of operation is very important, how can this be promoted by the right split of refinery operations.
(2) *Design Specification*: this includes the specification of the building and its facilities, e.g. dimensions, shape and layout of the control room.
(3) *Detailed engineering and construction*: this includes the specification of equipment and materials such as CRTs, lighting and furniture, followed by construction and installation.

The text of the agreement between ergonomists and the project owner is given below as an example of the arrangements that need to be made in this type of project.

3.1. *Definition of work stations and console operator tasks*

Information will be collected about responsibilities, tasks and communication in the existing control room. Preselected instrument and computer systems will be studied to determine possiblities and limitations in the man–console interface. Exxon Research and Engineering will give information on the on-site plants to be operated after completion of the project, including the number of control loops per process unit and interactions between the units.

The Ergonomics Group will then give recommendations about:

(1) the number of consoles;
(2) allocation of operator tasks to consoles;
(3) communication between control room operators and between control room operators and field operators and others; and
(4) communication and information facilities in the field.

The recommendations and the owners' decisions will be part of the Design Basis Memorandum (DBM).

3.2. *Size and nature of control room and control house*
After the design-basis phase, information will be collected about shape and dimensions of work-station components and their flexibility. Then the Ergonomics Group will build a mock-up of the essential parts of the control room. The mock-up will be evaluated with the input and assistance of the process operators as furture users. After discussions with the project owner and the interior architect, the ergonomists will give recommendations about:

(1) dimensions of the control room:
(2) location of work-stations in the control room;
(3) layout of offices in the control house; and
(4) layout of information and communication facilities in the control room.

Recommendations and decisions made by the project owner will be part of the Exxon Research and Engineering Design Specification.

3.3. *Console design and control room furnishing*
The ergonomists will comment ot the ergonomic aspects of the instrument and computer systems under consideration. This information will be used in the bid evaluation by the project owner. After selection of a system, a work-station mock-up will be realized and evaluated by, amongst others, process operators and maintenance personnel.

After discussion with the interior architect and the project owner, recommendations will be given about:

(1) work-station layout;
(2) other control room furniture;
(3) CRT screen glare minimization; and
(4) other environmental conditions (light, noise).

This contribution will be included in the detailed engineering.

4. Situation analysis and allocation of system tasks

After the project structuring a situation analysis was carried out in the existing conventional control room. In view of the level of process-unit integration, emphasis was laid on communication aspects. The specification of the UMS consisted of an instrument and control loop count for each operator job and an analysis of interconnecting process flows. The task analysis consisted of an intermittent observation of persons present in the control room (with an indication of their activities) and detailed observation of console operators during 50-minute periods (recording the number of discussions, communication with the field, acknowledgment of alarms, and interactions with displays and controls). Semi-structured interview were held with control room operators and shift supervisors.

4.1. *Results of the situation analysis*
The results showed a correlation of the amount of process-related communication of console operators and the number of process flows between operator consoles. The

existing work organization had a clear influence on communication. For instance, the communication pattern was influenced by an organizational splitting of the operators into two teams (for the first- and second-generation process units of the refinery). Furthermore, the impact of the use of the control room as a general information-gathering place and social centre was clearly shown. Finally, the situation analysis gave some insight into operator workload and positive job attributes.

The task analysis showed that operator workload was primarily determined by:

(1) communication with other consoles—the number of contacts is related to the number of process flows between consoles;
(2) communication with field operators—this correlates with the number of pertaining field jobs; and
(3) process supervision and control tasks—this cluster of operator tasks can be characterized by the number of control loops (automatic control valves).

These results were fed back to the reference committee and approved by them. A projection was then made about the future FLEXICOKER Refinery. Data were gathered on the type of process units, the number of process control loops, the integration of operations like process flows, heat integration, gas and steam balance, and the available new technology for instrumentation and computer systems.

4.2. *Task allocation and job design*

From the situation analysis and the projection of future requirements the following concept was developed:

(1) combine units in a way that the console can run its own shop as much as possible taking into account the maximum console operator workload;
(2) communication among consoles had to be encouraged in relation to the process flows among the consoles; and
(3) avoid activities in the control room which can be done elsewhere.

Facilities were created for activities that were moved outside the control room such as CRTs for engineers in adjacent rooms and in offices in the administration building, in plant houses for field operations equipped with CRTs and facilities for work permits and daily meetings with maintenance technicians.

For the operator jobs some detailed criteria could be formulated.

(1) A good trade-off between the three task elements mentioned before. The starting point for determining the overall workload was the workload of one of the existing control room jobs (200 control loops, 56 interconnecting process flows and 3·5 operator jobs in the field).
(2) A maximum of four field jobs per console, in view of communication load as well as training requirements and operator career line.
(3) A total of 150 to 250 control loops, depending on the other two task elements.
(4) New instrumentation and computer systems were expected to decrease physical workload and increase mental workload, both related to the replacement of parallel by sequential information presentation.

After several discussions on operator workload and manpower issues, a final agreement of five control room operator positions was reached. After this decision, individual process units had to be allocated to operator consoles (individual jobs). A proper balance between the three job elements had to be found such that the number of

important and critical process interactions between consoles was more or less minimized. Options were tested on an impact due to possible future refinery expansion. The final choice was also based on a reasonable geographical distribution of process units over the plant area.

In addition, a first design criterion for the control room layout could be formulated: consoles with fewer interactions were to be placed further from each other than those with more interactions.

4.3. *Mock-up evaluation*

Two different layouts were selected for a mock-up study. A description of the mock-up studies is given in Pikaar *et al.* (1985).

A full size mock-up, using simple materials (tables, wooden modules for CRTs with photographs of displays mounted on it, panels and paper), was realized for three operator work stations. The mock-up was constructed in a flexible way to enable several positions and shapes of the console to be examined.

The evaluation took two days. On the first day the control room project team worked with the mock-up, followed on the second day by the reference committee and shift supervisors. The participants were guided through the alternatives; questionnaires were used to gather their opinions. Finally, the participants were given an opportunity to rearrange the layout and console shape. At the end of the session, plenary discussions were held to draw conclusions. The discussions were run completely by the operators themselves. Consensus was reached in a short time, with satisfactory results. The second mock-up session took place several months later and concerned the detailed console design.

5. Comments of the project manager

In this section an overview of the ergonomic impact on the control room design is given from the point of view of the project manager. A major concern of the overall FLEXICOKER project team was how to keep the control room project within budget and on time schedule. Normally, very little time is spent to the design basis for control rooms. The number of process units, instrumentation and computer facilities determined the number of square metres and cubic metres of the building under standard architecture.

The first decision to be made was 'Should there be one control room with the latest instrumentation and computer technology or two control rooms, the existing one for the old units plus an additional one for the new units?' This decision had to be made without time to carry out a situation analysis. The initial idea was to have two control rooms, because this would be less expensive. However, considering the available time for communication and reaction times needed to avoid extra operational problems during upset or start-up operations, and its impact on process reliability and plant service, it was decided to have one central control room. In addition, the aspect of a greater flexibility to reshuffle and integrate old and new units over consoles was considered. The contribution by the ergonomists was mainly their 'know-how' of human communication and social behaviour.

Other decisions concerned key questions such as:

(1) how to divide the refinery operations into easily controllable groups;

(2) how to assign process units to these groups;
(3) which activities of field operators and support groups (process engineers, mechanics) should take place in the control room, in the control centre but not in the control room, or outside the control centre (e.g. in plant houses).

From the situation analysis it became clear that there was ample room for improvement of the existing situation: better operations with less control room operators.

The most difficult aspect to establish was the maximum job load, because the impact of the new instrumentation and computer systems could not be easily compared with situations elsewhere. Most of the information needed had to be estimated as the FLEXICOKER project was not yet in the design phase. Finally, it was decided to go for five consoles manned with one operator each, where we had started the discussion with eight consoles. Old and new process units, including utilities, were mixed.

The main contributions of the ergonomists during the development of the design basis were, as seen from the project managers point of view:

(1) restructuring of activities (task elements) and communications with regard to process operations; and
(2) quantification of job-load factors.

Moreover, arising from the contributions of the ergonomists, there was a growing awareness within the project team of the link between control room issues and the organization set-up. A few examples of this were:

(1) the design of console oriented work teams for the process sections with support from technical and maintenance groups;
(2) integration of console operators in one shift with one supervisor; and
(3) balanced console/field operator ratio with a technician liaison.

In the design specification phase the mock-up evaluations played a major role. During these evaluations it was possible to establish the layout of the control room and the shape of the consoles.

The situation analysis had shown us that eye-to-eye contact among console operators was important for team behaviour. This was used in the console design by openings in the console, the height of the console and by avoiding situating back-up instrumentation on the wall. Although each console operator had his own set of process units to control, he became, by design, a member of the control room team also.

The additional investment for the consolidation of the old and new control rooms was justified by the increased reliability and efficiency. The size of the computer room building was set by the dimensions of the computer room and instrumentation room. The control room and the related office space did not really impact on the cost of the building. The total investment for the control centre, including consoles but excluding computer and instrumentation, was slightly over US $8 million. The total cost of the ergonomic consultancy (including building the mock-ups) was estimated at US $0·1 million. The project took four years from initial conception to mechanical completion:

(1) Design Basis—analysis old control room 9 months,
—projection future refinery 12 months;
(2) Design Specification 6 months; and
(3) detailed engineering and construction 21 months.

In the design-basis phase, lack of information on the future process units and their level of integration was the limiting factor. The control room had to be completed about 1–1·5 years before the start-up of the FLEXICOKER as the utilities had to be available early. Therefore, detailed engineering and construction were continuously under pressure, but finally had no impact on the overall schedule.

6. Some comments of an ergonomist

The organizational structure of the design project with its design project team, including ergonomic advisors, the reference committee and a project owner with final responsibilities, is suitable to realize an ergonomics input. That is, provided ergonomists also meet design deadlines and have a (very) good understanding of the technical issues involved. Amongst other factors, doing a situation analysis, is of great value in getting acquainted with the project and the technical processes at hand.

Daily contact between ergonomists and the design project team were organized via the shift supervisor (member of the project team), which proved to be very fruitful. Among other things this enabled direct communication about operational details.

In an early phase of the project the integration of ergonomics was explained to Exxon Research and Engineering (USA) and their commitment was obtained.

Our presence during the situation analysis in the control room stimulated discussions in the shifts. The operators were interested in our opinions as external consultants (non-company employees) on the design. In particular the evening and night shifts proved to be very informative, probably for both shift members and ergonomists.

As stated by the project manager, the discussions on the number of control room operator jobs and their workload were of major importance during the project. Results of the situation analysis, opinions of the reference committee, and the presence of scientific researchers influenced the decision-making process.

It should be noted that the number of operator positions in the control room did not increase even though the number of process units almost doubled. One might expect serious problems with shift members on this manpower issue. However, among other things, the presentation of the situation-analysis results and discussion of the background information with the reference committee during the mock-up sessions probably enabled the operators to understand the validity of the job design.

The ergonomic approach to system design fitted well with the time schedule of the project phases. Ergonomic aspects could be included in the Design Basis Memorandum and the Design Specification. However, the time span available for the analysis was rather limited. That is the situation analysis made during normal process operations could easily be carried out within the time available (9 months). However, it was also felt there should be information on situations with off-normal operations like a start-up (planned) or a major upset (not planned). An analysis during a start-up period could only be carried out at the very end of the 9-month period mentioned above.

7. Some comments of the interior architect

This section gives the experiences of the interior designer. The interior design consultant joined the engineering contractor in October 1983, shortly before the detailed console mock-up session. Because the assignment could not be defined as a

measurable objective, the job started with a limit of 200-hours consultation at short notice. It came to an end after 2500-hours consultation, over 2·5 years later.

7.1. *Interior design and ergonomics*

Ergonomics and interior design are likely to have a few things in common. Practitioners are necessarily used to explaining what they do by profession and it is difficult to determine what the benefits are. In both cases there are, in the process of realization of ideas and advice, many people involved in a continuing attempt to make something totally different.

Working amongst technicians, the interior designer started with the benefit of the doubt which turned into a certain confidence as soon as the approach appeared to be valid and checkable. Here the approach mainly consisted of making proposals in balance with the actual phase of the project, with reference to given standards (for instance ergonomics) and without running ahead of details to come.

Besides doing the 'product' design, in a complex project like this it appears to be necesssary to watch production at the subcontractor level meeting design standards and deadlines on delivery. A major problem is to maintain coherence between the tremendous amount of different aspects. This cannot be solved by specifications in drawings or writing only, nor should the designer dictate how to deal with workmanship. On the other hand, the decisions of a creative technician at some place in a production line can be in conflict with the original ergonomic requirements, which he certainly does not know. This is not a plea to make the designer responsible for everything, but their involvement in the follow-up would be helpful.

7.2. *The interior design practice*

The interior design assignment concerned two items: the operator work-station design and the architectural design of the work environment. The project started with the architectural part in cooperation with the contractor construction department. In the engineering process of a petrochemical plant, architecture and aesthetics are usually not considered of primary importance. Therefore, it was decided to make design items calculable as much as possible. A human scale unit of measure was introduced, fitting it into the already established construction based building module. This enabled the construction department to work out separately a great number of building details without conflicting with interior design in later stages. The design purpose of this unification was to keep control over a variety of design decisions yet to be made throughout the building.

After a first acquaintance with the reference committee and an introduction to existing control rooms as a reference of what it should not be, the leading ideas were formulated on how to design the work environment. The given fact of physical separation from the world outside, including a total absence of daylight, was considered to be the most important problem to solve. It was proposed to install an artificial lighting system that should follow the natural cycle of day and night. This system was required to compensate for the isolation from the outside world and to support eye adaptation for in- and out-going field operators. The local direct lighting is under individual control for individual work places, operator consoles and surrounding offices. It was also desirable to maintain a maximum transparency (windows) inside the building, including the control room. However, to avoid glare on CRT screens no windows were placed behind the consoles.

The console design was begun after the second mock-up session and after decisions on most of the equipment to be installed had been made. A basic module was set up. This module was related to the maximum allowed dimensions from the ergonomic requirements (for instance console height) and a hypothetical volume of the expected equipment. An important problem to be solved was glare on CRT screens. As long as the industrial design of monitor screens is apparently not in line with ergonomic requirements, the best attainable situation is glare minimization.

7.3. *The process of realization*

The coordination within the contractors organization and with the Esso Project Management Team was of high level. This appeared not to be the case for the subcontractors and sub-subcontractors. There is a lot of creative workmanship involved in the production process. Increasing distance from abstract design requirements increases the chance of deviations. The interior design consultation was extended to follow up on-site in a number of factories in Europe: sometimes to retrieve mutilated acoustical specifications from a ceiling manufacturer; sometimes to avoid delivery of the wrong lighting fixtures, changed to meet delivery schedule, but totally useless to meet the lighting requirements. The prizewinner of individual creativity was the French subcontractor who produced the consoles. About 15 sessions of technical supervision in Marseille were needed to meet both the original design and the time schedule. Another important reason for the consultant to be there was delayed decisions on secondary equipment that had to be installed without major changes in the overall design.

8. Users, their participation and the final result

From a users point of view, the ergonomics in the project must be seen against the background of a non-optimal functioning of the old control room. Analysis by means of interviews with the users was fundamental to the ergonomic approach. Success can only be achieved with the good cooperation of every user. To establish this cooperation, shift sessions were held and the operators were given a guarantee that the results of the situation analysis would be fed back to them and that all data collected by the ergonomists would be used without any reference to individual information. In addition, shift representatives would be allowed to participate in design decisions as far as they were relevant to the operators. All together, this approach led to good cooperation between users and ergonomists. Three topics of major importance to the shifts are discussed below.

8.1. *Lighting*

There were a number of problems with computer-screen glare. In the new control room the lighting conditions had certainly been improved. However, the design was not good enough. After the start-up some adjustments were needed (and carried out).

The new control house had to be blast proof for safety reasons. Therefore, there are no windows. After consulting all persons involved (operators and those persons having offices in the new building), offices were realized with large windows to the corridors. Sophisticated lighting was installed in the control room and the corridors. An outdoor-light (daylight) simulation was designed for the corridors.

8.2. *Undesired visitors*

From the situation analysis it became clear that the control room was on many occasions used as a place for social contact, amongst others between non-process staff, because it was easily accessible. Together with the experience from other process plants, it was decided to situate the control room on a first-floor level. This was intended as a threshold for all kinds of people who were looking for somebody or some information or just a shelter for the bad weather outside.

8.3. *Restrictions in communication*

Good communication is of major importance for the reliability and efficiency of the operation of integrated plants. Knowledge of factors influencing communication was gathered during the situation analysis. These factors, process flows, layout and work organization, had their influence on control-room design. Consoles having an interface of important process flows with each other are situated next to each other. Therefore, the 'utility' console was situated in the centre of half a circle of consoles. No intercoms are necessary; operators can see each other and can communicate directly. The design of the ceiling allows for clear communication, even though distances between the operators are over 7·5 m. As described in Section 4 the layout was based on a mock-up evaluation made by the reference committee.

8.4. *Experiences*

Involving a representative group of users in the design of a highly automated process control system is necessary if the final result is to be accepted by the users. It probably also contributes to achieving a situation in which the system functions in the way it was intended to do.

Within the first operational year, there occurred two severe electric current failures (from outside the refinery), which could be handled by the operators without damage to equipment or product loss. During these situations it was necessary to have a second console operator (for which situation the consoles were designed). Management is convinced that these situations could not have been handled without product loss (shut down) if there had been two control rooms, or if less attention had been paid to communication in the control room layout. In conclusion, it can be said that communication was taken into account rightly.

It also appears that the ergonomic efforts in the project contributed to the way in which the operators work as a team in the new control room. The operators consider the new control room to be of their own design. It can be said that even practical oriented persons, such as the on-site process staff and operators, are aware of the profits of an ergonomics approach to system design.

Two years after the start-up of the FLEXICOKER, an ergonomic evaluation of the new control room was carried out, applying the same methods as used for the situation analysis of the old control room. The control room operators are very content with their work environment. It is only with regard to the CRT screens that some glare problems can be noted. The new control room is a quiet place. The operators can communicate easily with each other. One by one field operators pay a visit to the console operator to discuss operations or for social contact. As far as this can be deduced from the analysis, during normal operation and unit start-up operations on two consoles, operator workload is of an acceptable level (see also the remark above on electrical current failures).

9. Conclusions

From the evidence provided by this project it may be concluded that it is possible to include both ergonomics and user participation in every design phase of a large-scale project without getting behind on time schedules and without overstepping available budgets. The ergonomic approach to system design fitted well with the time schedule of the design project phases. The way the project was structured, with its project team, reference committee and project owner with final responsibilities, was suitable for realizing an ergonomics input.

From the overview given by the project manager, it becomes clear that the information collected during the situation analysis was important in several decision-making processes. Useful design and engineering data could be derived from the situation analysis and the full-scale mock-up evaluations.

It was difficult to establish the maximum operator job load as the impact of new instrumentation and computer systems could not be easily compared with situations elsewhere. The ergonomic contribution to solving this problem consisted in quantifying job load factors and structuring the whole package of operator activities (task elements). Moreover, initiated by ergonomists, there was a growing awareness within the project team of the link between control room design and work organization design.

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