

Enhancing the availability and reliability of power plants through macroergonomics approach

M A Azadeh^{1,*}, A Keramati¹, I Mohammadfam² and B Jamshidnedjad¹

¹Department of Industrial Engineering - Faculty of Engineering - University of Tehran, Tehran, Iran

²Department of Environmental Management, Graduate College of the Environment science and research Groups, Islamic Azad University, Department of Occupational Health, Faculty of Health, University of Hamadan Medical Science. Hamadan, Iran

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This paper describes an integrated macroergonomics model for operation and maintenance of power plants. Statistical tests on questionnaire survey data shows the importance of total human factors on job pressure. An integrated approach based on interview methods, questionnaires, information flow analysis and anthropometric and environmental assessment is discussed. The integrated approach provides detailed knowledge about ergonomics, management and safety conditions of power plants. Highlight of this study is the employment of a total system approach based on integration of the traditional human factors engineering and macroergonomics considerations. The approach of this study is applied to an advanced thermal power plant.

Keywords: Anthropometry, Ergonomic, Information flow, Macroergonomics, Safety, Total human factors

Introduction

In complex manufacturing systems, without its upward integration with job of operators and organizational design of such systems, at best, it leads only to sub-optimization and, therefore, results in an inherent error- and failure-prone total system. Such a system, eventually, when faced with concatenation of certain events, would suffer from this 'resident pathogen'¹⁻³. Operators' error should be seen as the result of human variability, which is an integral element in human learning and adaptation⁴⁻⁷. Thus, human error occurrences are defined by the behavior of total human-task-organizational system. Mechanisms that optimize teamwork between operator and machine are one of the great technological challenges, which are to create an intellectual interface between human operators, machine and organizational structures. In fact, organizational errors are often the root causes of human errors and man-machine failures⁸⁻¹⁰. Therefore, the interface systems must be matched with operators' capabilities. In addition, there is a need for an integrated design between operators, machines, management and organization.

Ergonomic considers those factors of machine, design and work posture that affect the user interface and working conditions related to the job or task design. In a macroergonomics study, ergonomic factors are considered in parallel to organizational and managerial aspects of working conditions in context of a total system design. Moreover, it attempts to create equilibrium between, organization, operators and machines. It focuses on total "people-technology" systems and is concerned with the impacts of technological systems on organizational, managerial and personnel subsystems¹¹⁻¹⁴.

A holistic human factors program (macroergonomics) optimizes interface between operators, machines and organization by using teamwork, on-the-job training, reliable safety and ergonomics programs, well-defined procedures and effective management. This paper presents an integrated model, which would enhance the reliability, productivity and working conditions of power plants. This study is among the first to examine macroergonomics components and traditional ergonomic factors in power plants. Control rooms and maintenance department of A 4 by 440 MW thermal power plants were chosen as the case of present study.

Materials and Methods

An integrated approach, employed (Fig. 1) in this study, is based on: 1) Interview methods and

*Author for correspondence

Tel: 00989121221103; Fax: 00982166461680

E-Mail: ali@azadeh.com; aazadeh@ut.ac.ir

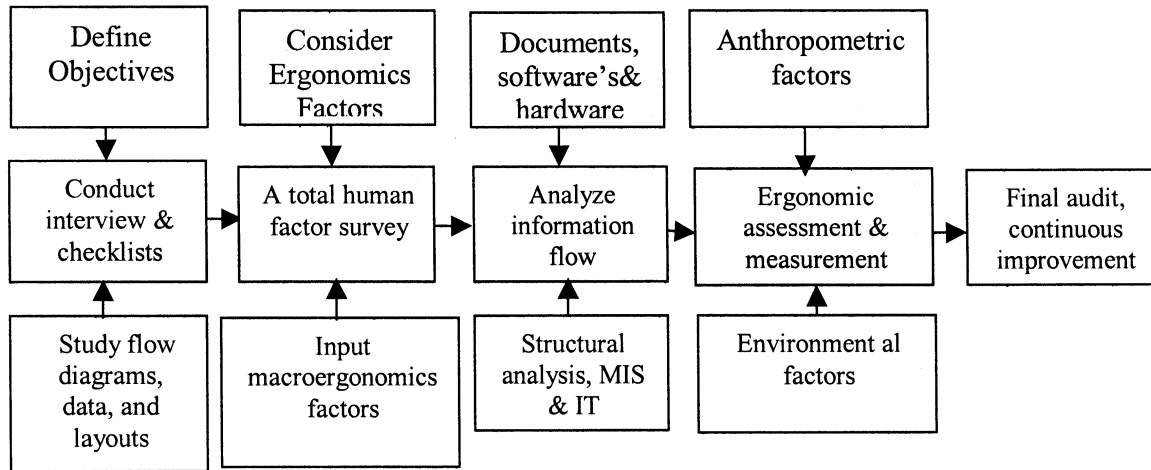


Fig. 1 — Macroergonomics approach

Table 1 — Sample questions from total human factors survey	
Typical questions	Category
How do you evaluate current information flow between control room and maintenance?	Information flow
Is there training about safety procedures & precautions?	Training
Do you need to memorize rules & procedures?	Procedures
Are you able to figure out what causes an accident?	Safety
Workload level during routine and emergency situations?	Workload & stress
Is there any financial reward for working as a team?	Motivation
Do you have difficulty with seating or standing positions?	Anthropometry
Are there pressures that could push you override safety precautions?	Safety
How is the quality of visibility of information in digital and analog display systems?	Display systems

checklists; 2) Questionnaires; 3) Assessment of documents and historical data; 5) Anthropometric and environmental measurements and analysis; and 6) Information flow analysis. Managers and operators are interviewed to exhibit their opinion about the working conditions and ergonomics considerations. A detailed questionnaire containing valuable information related to human factors, safety, environmental, management, teamwork and training

are developed and presented to operators. Anthropometric and environmental factors were measured and checked against standards. Finally, a final audit and a complete qualitative and quantitative analysis are performed to uncover hidden points¹⁵. The methodologies to achieve an integrated macroergonomics program require the following:

Total Human Factors Survey

Questionnaire was composed of 9 distinct groups: 1) safety; 2) rules and procedures; 3) training; 4) motivation; 5) stress and workload; 6) information flow and organizational structures; 7) environmental factors; 8) Anthropometric factors; and 9) display systems (Table1). Anthropometric and environmental section of the survey may contain information about working postures, height, weight, seating position, standing position, noise, light and pollution. This survey should give a general intuition of how the system being studied stands with respect to anthropometric and working standards. Moreover, critical factors in relation to working condition are introduced. For instance, most of the operators claiming moderate to high pain or tiredness in their hands could suggest improper height of workstations or unsuitable instruments, etc. Results must stress weak and strong points regarding the above factors.

Interview Method

Rules and procedures, operations and processes related to control room and maintenance are studied systematically. An effective and practical macroergonomics model should be designed for operators and supervisors of control rooms and

maintenance department. Therefore, managers and operators of the system being studied are required to be interviewed to exhibit their opinion about the working conditions and ergonomics considerations. It should bring about an introductory assessment of working conditions and ergonomic considerations. Interview techniques should cover the issues related to safety, teamwork, anthropometric factors, management and organizational factors, training and job satisfactions.

Ergonomics Measurements

Ergonomics measurements are categorized as anthropometric and environmental assessments. Environmental assessment considers factors of illumination and lighting, noise, temperature, humidity, and pollution. An anthropometric measurement is conducted in each single workstation. Also, equipment (workstation, panels, machines, etc.) layout in both control room and maintenance is analyzed to recommend a set of optimum solutions. The results should help locate stationary human factors' deficiencies besides safety and environmental issues.

Information Flow Analysis

This part examines the flow of information between control room and maintenance. In addition, interpersonal communication problems between operators and between operators and supervisors must be studied. This requires organizational and information structures including existing software's, hardware, information systems, level of hierarchy, procedures and documentation. The objective is to use all the formal means to uncover deficiencies in flow of information within and between departments. To achieve objectives, information flow diagram could be prepared. Documentation relating to work requests, work permits, and quality of communications are studied and analyzed. The results of this technique together with the findings of total human factors survey should enable to locate major deficiencies in regard to flow of information in control room and maintenance department.

Final Audit

A complete qualitative analysis was conducted to uncover hidden points in relation to safety and ergonomics issues. This phase acts as a final check against macroergonomics factors already discussed.

All previous findings are reviewed to expose hidden macroergonomics issues such as managerial or training problems. The system being studied must be carefully visited (station by station) to unveil hidden ergonomics and anthropometric issues.

Results and Discussion

Survey Method Results

This section presents the importance of total human factors including relationship between organizational procedures, co-workers, job design, teamwork and communication and information exchange, and usability design on job pressure, in context of human engineering in complex manufacturing systems. To present the importance of organizational procedures, co-workers, and job design, maintenance and operation operators of the power plant were divided into two groups of operators: 1) who believe there could be a better job design; and 2) who believe the current system of job design are okay. The two groups were tested with respect to job pressure, which is defined as workload level, time considerations and stress. Also, two groups of operators with and without inter-organizational issues and two groups of operators having and not having problems with organizational procedures were compared statistically.

Kruskal-Wallis Test

Kruskal-Wallis test performs an analysis that is very similar to an analysis of variance (ANOVA) on the ranks. The test is conducted when the assumptions for the parametric ANOVA cannot be made¹⁶. The test statistics is calculated using the following formula, which allows for different numbers of subjects in each of the two conditions:

$$H = \frac{12}{N(N+1)} \sum \frac{T_i^2}{n_i} - 3(N+1)$$

where N is the total number of subjects, n_i is the number of scores in each of the two condition, and T_i is the total of the rank in each of the two conditions. The calculated value of H is then compared with the table value of chi-square with 1 degree of freedom at the chosen level of significance to reject the null hypothesis¹⁶. Furthermore, it assumes independence between subjects in conditions. The general format of the test is as follows: 1) $H_{0(a)}$: The two groups of operators have the same performance with respect to job pressures; and 2) $H_{1(a)}$: Otherwise.

Table 2 — Significant level of test of comparison on the job pressures

Difference in mean ranking		Significant level α	Relative disadvantage %
Having problems with organizational procedures	No problem with organizational procedures	0.0009	50
Problems with co-workers due to inter-organizational issues	No problem with co-workers	0.0139	45
Believing a better job design is required	Believing current system is OK	0.0010	300

Operators having problems with co-workers due to inter-organizational issues report higher level (50%) of job pressures (Table 2). Operators who don't have any problem with organizational procedures report lower level of (45%) job pressures. In addition, operators who believe that there could be a better job design (the majority of operators) reported higher level (300%) of job pressures. Two other thermal power plants were examined and approx similar findings were echoed. This is an important finding, which reveals the current system of job design is partially rather than totally optimized. This is due to lack of human engineering factors when the current system of job design was designed and implemented. This means the existing system of job design must be re-engineered in context of human engineering.

The other factor, which has been statistically tested, is the association of teamwork and communication and information with job pressure. To present the importance of teamwork and communication and information exchange, the maintenance and operation operators of the power plant were studied by non-parametric statistical analysis. The Cramer's Phi statistic tests the null hypothesis ($H_{0(b)}$) of no correlation between the two variables against alternative hypothesis ($H_{1(b)}$) of correlation between the two variables¹⁷.

Cramer's Phi Coefficient

This coefficient is a correlation index for K by L matrices and its maximum value does not depend on the number of levels of variables (K and L). It is the extended version of Phi coefficient. The range of this coefficient¹⁷ regardless of the values of L and K is always between 0 and 1. If K and L are defined such that $L \leq K$, the Cramer's Phi coefficient is defined as:

$$\phi' = \sqrt{\frac{\chi^2}{n(L-1)}}$$

Table 3 — Test of correlation between job pressures and selected human engineering factors

Human engineering factors	Cramer's Phi	Significant level, α
Usefulness of informal information exchange	0.43	0.00017
Reward for teamwork by supervisors	0.55	0.00002
Supervisors' monitoring and assessment at work	0.40	0.00900

where the numerator value of chi-square is found from appropriate table with 2 degrees of freedom at the chosen level of significance, n is the total number of subjects and L is number of the levels of first variable. Above statistics would test null hypothesis (H_0) of no correlation between two variables against alternative hypothesis (H_1) of correlation between two variables.

The test of hypothesis of the non-parametric Cramer's Phi correlation between job pressures and teamwork and information exchange is in the following general format: 1) $H_{0(b)}$: The selected factors are not correlated with job pressures; and 2) $H_{1(b)}$: Otherwise. There is strong evidence that usefulness of information exchange is correlated with job pressures at work (Table 3). Lower job pressures are reported as the quality and usefulness of information exchange increases. Also, job pressure is positively correlated with teamwork. Operators who are rewarded for teamwork report lower level of job pressures and consequently produce higher performance. Supervisors' monitoring and assessment in context of information exchange system could also lower job pressures, because such data is constantly flowing between managers and employees. In summary, these findings suggest the positive impacts of teamwork and well-designed information exchange systems on human performance. Furthermore, there is

Table 4 — Test of correlation between job pressures and quality of information

TSD factor	Cramer's Phi	Significant level, α
Suitability of perceived information from supervisors	0.56	0.00000
Suitability of perceived information from co-workers	0.45	0.00008
Ease of contact with supervisors	0.50	0.00002

a need for an accurate reliable modern information system, which allows effective teamwork and information interchange between personnel.

The importance of usability design is the last total human factor, which is statistically tested in this study. The Cramer's Phi statistic tests the null hypothesis ($H_{0(c)}$) of no correlation between the two variables against alternative hypothesis ($H_{1(c)}$) of correlation between the two variables. Test of hypothesis of the non-parametric Cramer's Phi correlation between job pressures and suitability of perceived information and ease of contact is in the following format: 1) $H_{0(c)}$: The quality and suitability of information is not correlated with job pressures; and 2) $H_{1(c)}$: Otherwise. There is strong evidence that suitability (quality) of perceived information from co-workers and supervisors are correlated with job pressures (Table 4). Lower job pressures are reported as the quality and usefulness of perceived information increases. In addition, ease of contact is positively correlated with workload. Hence, enhancing ease of contact with supervisor seems to be lowering job pressures. Furthermore, an efficient user-friendly information exchange system may result in lowered workload. In summary, these findings suggest the positive impacts of user-friendly interface and well-designed information exchange systems on human performance. Furthermore, there is a need for user-friendly interfaces within electronic information systems, which allows easy visible information retrieval and effective communication between personnel.

Final Audit Results

The findings of final audit show several problems concerning macroergonomics factors. For instance, proper protective equipment was not worn and operators of a welding workstation violated safety

procedures. Power plant is at the stage of implementing the findings of this study and consequently improving productivity and reliability of the power plant. Some of the most important findings of the macroergonomics study in regard to safety, procedures, training, workload, motivation, information flow, environmental factors, anthropometric factors and display systems are listed as follows: i) Utilization of safe and conventional protective equipment in maintenance department; ii) Job pressures during emergency situations needs be balanced with the job of operators; iii) Noise level in and around control rooms needs be controlled to standard level iv) Lighting systems in both departments must be modified and standardized; v) Spread of teamwork and group think in control room is recommended (Indeed, an effective macroergonomics program requires teamwork between operators and managers at all levels. Teamwork has been shown to enhance the productivity and availability of power plants¹⁸); vi) Layout of few workstations in maintenance department must be redesigned; vii) A more stimulating program needs to be designed for night shift operators; and viii) Existing information system between control room and maintenance must be utilized more efficiently.

Conclusions

A well-defined and practical macroergonomics program requires teamwork between operators and supervisors at all levels. The integrated technique should be cautiously carried out to avoid local or short-term improvements. This requires a team of experts specializing in human factors, organizational design and statistics. Moreover, the experts should be familiarized with the idea of macroergonomics; which requires an intellectual interface between operators, machines and management. Therefore, human factors designers must use an integrated method to identify the gaps at various workstations and overlooked weak points. Every manufacturing manager be responsible for integrating people, machines and time^{19,20}. The manufacturing managers need to adopt a more systemic approach understanding the complex interrelationship in the system. Systemic understanding is difficult to achieve, but is necessary if one has to face with increasing uncertainties and competitions of manufacturing systems.

In present model, an integrated approach has been developed to study ergonomics and macroergonomics issues in complicated control systems. Specifically, advanced digital control equipments are utilized in control rooms and the extent of use of analogy control systems have been decreased over the recent years. Advanced technologies need new organizational infrastructures, which could be considered as macroergonomical aspects. It is proposed to study the macroergonomical aspects of technology as the future application of the present model.

References

- 1 Reason J, *Human Error* (Cambridge University Press, Cambridge) 1992, 53-125.
- 2 Perrow C, The organization context of human factors engineering, *Admin Sci*, **28** (1983) 521-541.
- 3 Meshkati N, Integration of workstation, Job and team structure design in complex human-machine system: A framework, *Int J Ind Ergon*, **7** (1991) 111-122.
- 4 Rasmussen J, Human sources of work complications, *Invited position paper for Conference on Human Error*, Stanford University, 1991.
- 5 Rasmussen J & Batstone R, Why do complex organization systems fail, in *World Bank Policy Planning and Research Staff* (World Bank, Virginia, USA) 1989, 121-127.
- 6 Rasmussen J, The role of error in organizing behavior, *Ergonomics*, **33** (1990) 1185-1199.
- 7 Azadeh M A & Hooshiar M, An integrated macroergonomics model to enhance the productivity and working conditions of an assembly shop, in *CSME Forum SCGM, 19-22 May 1998* (Ryerson University of Technology, Toronto, Canada) 1998, 819-828.
- 8 Pate-Cornell M E, Organizational context of human factors engineering system safety, *Science*, **250** (1990) 1210-1216.
- 9 Perrow C, *Complex Organization: A Critical Essay* (Random House, New York), 1986, 49-140.
- 10 Kawowski W, 1991, Complexity, fuzziness and ergonomics in compatibility issues in the control of dynamic work environment, *Ergonomics*, **34** (1991) 671-686.
- 11 Hendrick, H W, Future directions in macroergonomics, *Ergonomics*, **38** (1995) 1617-1624.
- 12 Hendrick, H W, Macroergonomics: a concept whose time has come, *Bull Hum Factors Soc*, **30**(2) (1987) 1-2.
- 13 Hendrick, H W, *Organizational design, Handbook of Human Factors* (John Wiley & Sons, New York) 1987, 54-175.
- 14 Azadeh M A, Integrating methods of enhancing reliability of manufacturing systems, in *1st Conf Fundamental & Industrial Research Achievements* (Faculty of Engineering, University of Tehran, Tehran, Iran) 1999, 17-27.
- 15 Bailey R W, *Human Performance Engineering* (Prentice Hall, New York) 1989, 17-160.
- 16 Hinton, P R, *Statistics Explained* (Routledge, New York) 1996, 32-97.
- 17 Hooman, H A, *Statistical Inference in Behavioral Research* (Parsa Press, Tehran, Iran), 1994.
- 18 Hart R, Whitaker M, Hughes H & Templet H P, Team concept to mitigate an MIC failure in a petrochemical plant cooling system, *Mat Performance*, **29** (1990) 40-44.
- 19 Azadeh, M A, Creating high reliable manufacturing systems, in *Int Conf Reliability, Maintainability & Safety*, Shanghai, China, 1999.
- 20 Drucker P E, Emerging theory of manufacturing, in *Harvard Business Review*, 1990, 94-101.