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Macroergonomics, which emerged historically after sociotechnical systems theory, quality management, and ergonomics, is presented as the basis for a needed integrative methodology. A macroergonomics methodology was presented in some detail to demonstrate how aspects of microergonomics, total quality management (TQM), and sociotechnical systems (STS) can be triangulated in a common approach. In the context of this methodology, quality and safety were presented as 2 of several important performance criteria. To demonstrate aspects of the methodology, 2 case studies were summarized with safety and quality performance results where available. The first case manipulated both personnel and technical factors to achieve a "safety culture" at a nuclear site. The concept of safety culture is defined in INSAG-4 (International Atomic Energy Agency, 1991). as "that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance." The second case described a tire manufacturing intervention to improve quality (as defined by Sink and Tuttle, 1989) through joint consideration of technical and social factors. It was suggested that macroergonomics can yield greater performance than can be achieved through ergonomic intervention alone. Whereas case studies help to make the case, more rigorous formative and summative research is needed to refine and validate the proposed methodology respectively.

ergonomics and quality   macrorgonomics   work system design

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1. INTRODUCTION

1.1. Background

Sociotechnical systems (STS) theory, ergonomics, and total quality management (TQM) all emerged in response to World War II, which resulted in mass devastation in Europe and the Far East. The War also exemplified numerous mismatches of human and machine, leading to the formalization of ergonomics. Many years later, due to trends in technology, demographics, and competition, the Human Factors Society (now, the Human Factors and Ergonomics Society) formed a "Select Committee on Human Factors Futures, 1980–2000" to study these trends and determine their implications for the human factors discipline. Macroergonomics, or work system analysis and design, emerged formally in the 1980s in response to this study (Hendrick & Kleiner, in press). Specifically, macroergonomics, which uses the STS theoretical framework, is the starting point for effective microergonomics and offers a validated methodology for implementing or enhancing TQM. This integrative approach, integrating ergonomics, TQM, and STS, naturally leads to improved safety and quality, which are seen as dependent measures related to system performance criteria.

1.2. Sociotechnical Systems Theory

Following World War II, the sociotechnical Tavistock School of the UK integrated the structural and human perspectives of organizational and job design to enable large scale industrial improvement. Sociotechnical systems theorists sought to expand operators' knowledge of social and economic consequences; treat the work system as the unit of analysis; jointly optimize the social and technical subsystems; and maintain self regulation and redundancy of skills in work systems (Emery & Trist, 1965). Sociotechnical systems theory is supported by several core constructs, including joint causation, joint optimization, and joint design.

Joint causation refers to the belief that the personnel and technological subsystems (i.e., the sociotechnical work system) are jointly affected by or are open to the environment. The environment acts as both a resource provider to the work system as well as an evaluator of the work system (Pasmore, 1988) and environmental forces permeate the organization

(Davis, 1982). Joint causation leads to the related sociotechnical systems theoretical concept of joint optimization. The conversion or transformation of inputs to outputs requires both personnel and technology. The former is comprised of the people who perform the work and the latter of the way in which they perform the work through tasks, methods, tools, information, machinery, and equipment. Whereas pure sociotechnical systems theory implies equal weighting to both subsystems, from an ergonomic standpoint, once the technology is designed, it is relatively fixed. Therefore, in practice, people are expected to adapt to the technology or perform "left-over" functions. As will be seen later, the macroergonomic operational definition of joint optimization then is to consider human capabilities and limitations in order to achieve joint optimization. Optimizing one subsystem and fitting the second to it results in suboptimization of the joint work system. Historically, the tendency has been to optimize the technology, even by sociotechnical researchers (Taylor & Felton, 1993). Therefore, maximizing overall work system effectiveness, including safety and quality, requires jointly optimizing both subsystems.

Joint optimization then requires the joint design of the technical and personnel subsystems in order to develop the best possible fit between the two, given the objectives and requirements of each, and of the overall work system (Davis, 1982). Inherent in this joint design process is developing an optimal structure for the overall system as well. In this regard, considerable attention has been given to organizational design in sociotechnical systems practice. Although, a detailed discussion of organization design is beyond the scope of this article, such factors as complexity (i.e., differentiation and integration), centralization, and formalization should be optimized with respect to characteristics of the environmental, technological and personnel subsystems according to the theoretical framework.

1.3. Quality and Total Quality Management

Before the total quality control (TQC) and total quality management (TQM) movements, traditional quality control approaches focused on controlling the quality of system inputs and outputs through sampling and inspection methods. Feigenbaum (1961), Deming (1986), and others emphasized the need to control in-process quality as well and TQM led to an emphasis on supplier certification of quality and customer satisfaction.

At the conclusion of the War, Deming agreed to apply his statistical knowledge in Japan in order to help assist the ravaged nation with their reconstruction efforts. In the decades following the War, Deming's methods have become recognized as a cornerstone of the modern TQM movement. This movement began in the USA in the early 1980s in Defense and continues today across all sectors. Consistent with the STS view of organizations, Deming (1986) claimed his systems flow diagram and view of Japanese manufacturing organizations began the island nation's transformation process. Deming's approach illustrated the importance of participative decision making in organizational performance (Walton, 1986), which was also quite consistent with the sociotechnical systems emphasis on autonomy and decentralized decision making. Deming's approach suggested for a system to be optimized, the aim of the total system should drive decision making, including decisions aimed at improving the system's processes.

Today, Total Quality Management refers to a variety of team-based programs and approaches that aim to continuously improve performance through the continual improvement of processes. They utilize various "quality tools" and cross-functional process improvement teams. There are three central or core values in TQM: teamwork, customer focus, and continuous improvement of processes through data collection, measurement, and analysis (Kleiner & Hertweck, 1996). It is suggested that TQM emerged and is maintained essentially as a practitioner phenomenon. Only in the past few years have management and quality control scholarly journals embraced TQM. In the USA, some measure of validation was achieved in the late 1980s when the well-respected National Science Foundation (NSF) created a research program entitled "Transformations to Quality Organizations" for TQM research projects resulting from University-Industry partnerships.

As Taylor and Felton (1993) have suggested though, whereas TQM precepts are consistent with STS, STS offers the umbrella under which TQM (as well as other intervention strategies) belongs. In terms of teamwork, STS goes beyond the semi-empowered cross-functional team of TQM to organize autonomous work teams. STS goes beyond customers and customer satisfaction to understand, evaluate, and improve all stakeholder interactions.

And finally, the TQM principle of continuous improvement was promoted as the STS design principle of "incompletion" decades ago. Therefore, for the purpose of this paper, quality is defined as a dependent

Traditional checkpoints included inputs and outputs. TQC and TQM movements have added emphasis on in-process, supplier, and customer checkpoints (Kleiner, 1997).

1.4. (Micro) Ergonomics and Macroergonomics

In response to specific safety concerns experienced in World War II, ergonomics was formalized as a way to address human capability and limitation in system design (Chapanis, 1965). The unique technology of the ergonomics profession is *human-system interface technology* (Hendrick & Kleiner, in press). Historically, activity centered around this technology has produced interface design principles, guidelines, specifications, methods, and tools in the interest of improving the human condition, including health, safety, comfort, productivity, and quality of life (Hendrick & Kleiner, in press).

Whereas microergonomics has certainly had its impact during and since World War II, the Select Committee of the Human Factors Society revealed that by 1980, three dysfunctional design practices or shortcomings were prevalent: technology-driven design, a left-over function allocation approach for human tasks and functions, and a failure to incorporate all of the relevant sociotechnical factors in system design. In short, microergonomics was not realizing its full potential.

Macroergonomics was institutionalized as a means to address the shortcomings of system design in the interest of achieving greater performance improvements from ergonomic interventions, including gains in safety and quality. In short, it has been contended and demonstrated that macroergonomics leads to better microergonomics (Hendrick, 1997; Hendrick & Kleiner, in press). Macroergonomics is a formal subdiscipline of ergonomics and human factors. It is also supported by empirical science. From its foundational research roots in the sociotechnical systems tradition to modern laboratory investigation of the relationship among technological, personnel, organizational design, and environmental variables and their interactions, new scientific knowledge about work systems and work system design has emerged. Consistent with the empirical research in this area, macroergonomic methodologies for analysis and design of work systems have been developed to achieve systemic improvements in performance. One such methodology is now presented.

2. MACROERGONOMICS METHODOLOGY

2.1. Background

The following methodology has been developed based on the writings of Emery and Trist (1978), Taylor and Felton (1993), Clegg, Ravden, Corbertt, and Johnson (1989), and the author's own experience with large scale change in academia, industry, and government (Kleiner, 1996) with specific emphasis on integrating sociotechnical systems theoretical propositions and prescriptions with microergonomics. Essentially, sociotechnical systems approaches did not directly address microergonomics issues and microergonomics historically failed to address the larger system's environmental and organizational issues. Macroergonomics and this methodology integrate these concerns. In this particular description, safety and quality are highlighted and emphasized.

2.2. Scanning the Environmental and Organizational Design Subsystems

The first phase of sociotechnical analysis of work system process is to scan the system, then the environment, and organizational subsystems. As the external environment, operating under joint causation, may be the most influential subsystem in determining whether the sociotechnical system will be successful, achieving a valid organization and environment fit and joint optimization is essential.

Within the system scan, there is often a gap between what the organization professes as its defining characteristics and its actual identity as observed from organizational behavior. It is instructive to assess the nature and extent of this variance. To do this, the formal company statements about mission (i.e., purpose), vision, and principles are identified and evaluated with respect to their components. Specifically related to safety and quality, it is instructive to see whether and to what extent the organization places emphasis on these criteria. For example, is the welfare of employees emphasized in the professed of values or guiding principles? Does the mission statement speak of "quality" products or processes?

System scanning involves defining the workplace in systems terms including defining relevant boundaries. Several tools are available to assist with scanning. The organization's mission is detailed in systems terms (i.e., inputs, outputs, processes, suppliers, customers, internal controls, and feedback mechanisms). The system scan also establishes initial boundaries of the work system. As described by Emery and Trist (1978), there are throughput, territorial, social, and time boundaries to consider.

Entities outside the boundaries identified during the system scan are part of the external environment. In the environmental scan, the organization's subenvironments and the principle stakeholders within these subenvironments are identified. Their expectations for the organization are identified and evaluated. Conflicts and ambiguities are seen as opportunities for process or interface improvement. Variances or unwanted deviations are evaluated to determine design constraints and opportunities for change. The work system itself can be redesigned to align itself with external expectations or conversely, the work system can attempt to change the expectations of the environment to be consistent with its internal plans and desires. According to STS theory, the response in part will be a function of whether the environment is viewed by the organization as a source of provocation or inspiration (Pasmore, 1988). In our experience, much of the time the gaps between work system and environmental expectations are gaps of perception and communication interfaces need to be developed between subenvironment personnel and the organization. Design focuses on design or redesign of interfaces among the organizational system and relevant subenvironments to improve communication and decision making. These interfaces are referred to as organization- or work system-environment interfaces.

It is useful to develop organizational design hypotheses based upon the environmental and system scans. By referring to the empirical models of the external environment (Hendrick & Kleiner, in press), optimal levels of complexity (both differentiation and integration), centralization, and formalization can be hypothesized.

2.3. Production System Type and Performance Expectations

The work system's production type can help determine optimal levels of complexity, centralization, and formalization. The system scan performed in the previous phase should help in this regard and the analyst should consult available production models. In this context, key performance criteria related to the organization's purpose and technical processes are identified. This requires a determination of success factors for products and services, but may also include performance measures at other points in the organization's system, especially if decision making is important to work process improvement. As described in Kleiner's (1997) framework adapted from Sink and Tuttle (1989), specific standardized performance criteria guide the selection of specific measures that relate to different parts of the work process. Measures can be subjective, as in the case of self reports, or measures can be objective, measured from performance.

Once the type of production system has been identified and the empirical production models consulted, the organizational design hypotheses generated in the previous phase should be supported or modified until the personnel subsystem can be thoroughly analyzed as well. In terms of function allocation, requirements specifications can be developed, including microergonomic requirements at this juncture. Also included are system design preferences for complexity, centralization, and formalization. Clegg et al. (1989) also suggested the use of scenarios that present alternative allocations and associated costs and benefits.

2.4. Unit Operations and Work Process

Unit operations are groupings of conversion steps that together form a complete piece of work and are bounded from other steps by territorial, technological, or temporal boundaries. Unit operations can often be identified by their own distinctive subproduct and typically employ 3–15 workers. They can also be identified by natural breaks in the process, that is, boundaries determined by state changes (transformation) or actual changes in the raw material's form or location (input) or storage of material. For each unit operation or department, the purpose, objectives, inputs, transformations, and outputs are defined. If the technology is complex, additional departmentalization (horizontal differentiation) may be necessary. If collocation is not possible or desirable, spatial differentiation and the use of digital integrating mechanisms may be needed. If the task exceeds the allotted schedule, then work groups or shifts may be needed. Ideally, resources for task performance should be contained within the unit, but interdependencies with other units may complicate matters. In these cases, job rotation, cross training, or relocation may be required.

The current workflow of the transformation process (i.e., conversion of inputs to outputs) should be flow charted, including material flows, workstations, and physical as well as informal or imagined boundaries. In linear systems such as most production systems, the output of one step is the input of the next. In non-linear systems such as many service or knowledge work environments, steps may occur in parallel or may be recursive. Unit operations are identified. Also identified at this stage are the functions and subfunctions (i.e., tasks) of the system (Clegg et al., 1989). The purpose of this step is to assess improvement opportunities and coordination problems posed by technical design or the facility. Identifying the work flow before proceeding with detailed task analysis can provide meaningful context in which to analyze tasks. Once the current flow is charted, the macroergonomist or analyst can proceed with a task analysis for the work process functions and tasks.

2.5. Variances

A variance is an unexpected or unwanted deviation from standard operating conditions, specifications or norms. STS distinguishes between input and throughput variances. For throughput variances, Deming (1986) distinguished between special or common causes of variation, the former being abnormal causes and the latter expected system variation from normal operations. Special variances need to be tackled first to get the work process in control, at which time common variation can be tackled for overall system improvement. For the ergonomist, identifying variances at the process level as well as the task level can add important contextual information for job and task redesign to improve safety and quality performance. By using the flowchart of the current process and the detailed task analysis that corresponds to the flow chart, the macroergonomist or analyst can identify variances.

2.6. Variance Matrix

Key variances are those variances that significantly impact performance criteria and may interact with other variances thereby having a compound effect. The purpose of this step is to display the interrelationships among variances in the transformation work process to determine which ones

TABLE 1. Variance Matrix Example

Unit Operations		Variances
Formal Directive to Initiate Work	1	Written directive is distributed to suppliers
	2	Directive received by suppliers
	3	Complexity of directive
	4	Correctness of directive
	5	Timeliness of directive
Design of Product	6	Availability of design team
	7	Time allowed for design
	8	Completeness of directive
	9	Complexity of directive
Development of Product	10	Timeliness of transaction
	11	Completeness of design
	12	Complexity of design
	13	Availability of development team
	14	Accuracy of design
Manufacturing of Product	15	Availability of machinery
	16	Time required to produce
	17	Availability of materials
	18	Accuracy of product specifications
	19	Timeliness of request
Testing of Product	20	Accurate creation of product
	21	Availability of testing equipment
	22	Required number of tests
	23	Material tolerances
Certification of Product	24	Accuracy of test results
	25	Accuracy of test reporting
Review of Certificate	26	Timeliness of transaction
	27	Changes to product specifications
	28	Matching tolerances
Presentation of Product	29	Timeliness of information relay
	30	Accuracy of information
Preflight Readiness Review	31	Timeliness of information dissemination
	32	Accuracy of information
	33	Accuracy of system integration
Establishment of Mission Management Team	34	Availability of team members
	35	Cooperativeness of team

affect which others. The variances should be listed in the order in which they occur down the vertical y axis and across the horizontal x axis. The unit operations (groupings) can be indicated and each column represents a single variance. The analyst can read down each column to see if this variance causes other variances. Each cell then represents the relationship between two variances. An empty cell implies two variances are unrelated. The analyst or team can also estimate the severity of variances by using a Likert-type rating scale. Severity would be determined on the basis of whether a variance or combination of variances significantly affect performance. This should help identify *key variances*. A variance is considered *key* then if it significantly affects quantity of production, quality of production, operating costs (utilities, raw material, overtime, etc.), social costs (dissatisfaction, safety, etc.), or if it has numerous relationships with other variances (matrix). Typically, consistent with the Pareto Principle, only 10–20% of the variances are significant determinants of the quality, quantity, or cost of product. Interestingly, the control of in-process quality and the associated statistical quality control methods as popularized by Deming, are remarkably similar to the notion of controlling throughput variances. Table 1 illustrates a variance matrix.

2.7. Key Variance Control Table and Role Network

The purpose of this phase is to discover how existing variances are currently controlled and whether personnel responsible for variance control require additional support. The Key Variance Control Table includes the unit operation in which variance is controlled or corrected; who is responsible; what control activities are currently undertaken; what interfaces, tools, or technologies are needed to support control; and what communication, information, special skills, or knowledge are needed to support control. A *job* is defined by the formal job description, which is a contract or agreement between the individual and the organization. This is not the same as a *work role*, which is comprised of actual behaviors of a person occupying a position or job in relation to other people. These role behaviors result from actions and expectations of a number of people in a role set. A *role set* is comprised of people who are sending expectations and reinforcement to the role occupant. *Role analysis* addresses who interacts with whom, about what, and how effective these relationships are. This relates to technical production and is important because it determines the level of work system flexibility.

In a role network, first the role responsible for controlling key variances is identified. Although multiple roles may exist that satisfy this criterion, there is often a single role without which the system could not function.

With the focal role identified within a circle, other roles can be identified and placed on the diagram in relation to the focal role. Based upon the frequency and importance of a given relationship or interaction, line length can be varied, where a shorter line represents more or closer interactions. Finally, arrows can be added to indicate the nature of the communication in the interaction. A one-way arrow indicates one-way communication and a two-way arrow suggests two-way interaction. Two one-way arrows in opposite directions indicate asynchronous (different time) communication patterns. To show the content of the interactions between the focal role and other roles and an evaluation of the presence or absence of a set of functional relationships for functional requirements, labels are used to indicate the **G**oal of controlling variances; **A**daptation to short-term fluctuations; **I**ntegration of activities to manage internal conflicts and promote smooth interactions among people and tasks; and **L**ong-term development of knowledge, skills, and motivation

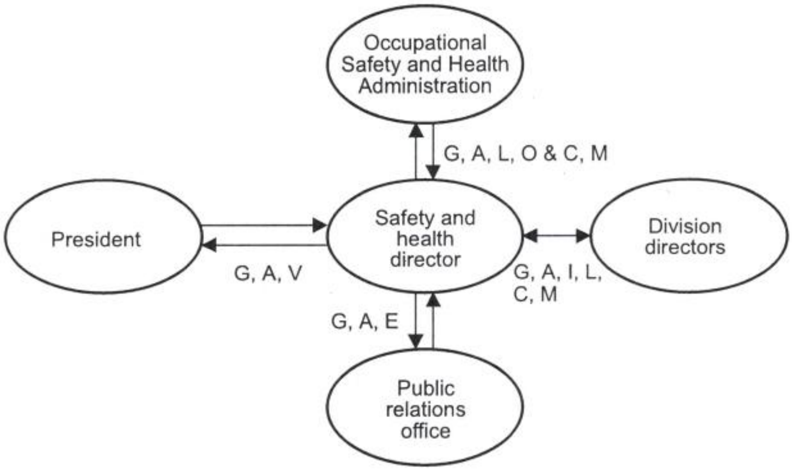

Figure 1. Example role network. *Notes.* A—**A**daptation to short-term fluctuations; C—**C**ross-boundary; E—**E**qual or peer; G—**G**oal of controlling variances; I—**I**ntegration of activities to manage internal conflicts and promote smooth interactions among people and tasks; L—**L**ong-term development of knowledge, skills, and motivation in workers; N—**N**onsocial; O—**O**utside; V—**V**ertical hierarchy.

in workers. Also, the presence or absence of particular relationships is identified as Vertical hierarchy; Equal or peer; Cross-boundary; Outside; or Nonsocial. Figure 1 illustrates a role network.

The relationships in the role network are then evaluated. Internal and external customers of roles can be interviewed or surveyed for their perceptions of role effectiveness as well. Also, the organizational design hypotheses can be tested against the detailed analysis of variance and variance control. The role analysis and variance control table may suggest, for example, a need to increase or decrease formalization or centralization. If procedures are recommended to help control variances, this increase in formalization must be evaluated against the more general organizational design preferences suggested by the environmental and production system analyses.

2.8. Function Allocation and Joint Design

Having previously specified system objectives, requirements, and functions it is now time to systematically allocate functions and tasks to human and machine or computer. It is helpful to review the environmental scan data to check for any subenvironment constraints (e.g., political, financial, etc.) before making any mandatory allocations (Clegg et al., 1989). Next, provisional allocations can be made to the human(s), machine(s), both, or neither. In the latter case, a return to developing requirements may be appropriate using four groups of criteria: technical feasibility; health and safety; operational requirements (i.e., physical, informational, performance); and function characteristics (i.e., criticality, unpredictability, psychological). See Kleiner (1998) for a review of macroergonomic directions and issues in function allocation.

Technical changes are made to at best, prevent or at worst, control key variances. Human-centered design of the following may be needed to support operators as they attempt to prevent or control key variances: interfaces; information systems to provide feedback; job aids; process control tools; more flexible technology; redesign work station or handling system; or integrating mechanisms.

After considering human-centered system changes in the previous step, it is time to turn our attention to supporting the person directly by addressing knowledge and skill requirements of key variances and any selection issues that may be apparent. In the variance control table, we identified who controls variances and the tasks performed to control these variances. At this stage, we suggest personnel system changes to prevent or control key variances. This may entail specific skill or knowledge sets that can be acquired through technical training, formal courses, workshops, or distance learning.

At this point in the process, organizational design hypotheses have been generated and iteratively adjusted as new analyses are performed. It is now time to take the specifications for organizational design levels of complexity, centralization, and formalization and produce specific structures. Depending upon the level of work system process analysis, this may require design or redesign at the organizational level, or at the group or team level, or at both levels.

2.9. Roles and Responsibilities Perceptions

It is important to identify how workers *perceive* their roles documented in the variance control table, especially if the table was initially constructed by those who do not occupy the roles identified. Through interviews, role occupants can participate in an analysis of their perceptions of their roles. Using the previously constructed table, expected roles, perceived roles any variances can be identified. Variances can be managed through training and selection as well as technological support. Essentially, two role networks are operating, the one needed and the one perceived. Any variation between the two can be reduced through participatory ergonomics, training, communication, interface design, or tool design.

2.10. Design or Redesign Support Subsystems and Interfaces

Consistent with the STS design principle, "support congruence" (Taylor & Felton, 1993), now that the work process has been analyzed and jointly designed, other internal organizational support subsystems may require redesign (e.g., management system, and reward system, maintenance). The goal is to determine the extent to which a given subsystem impacts the sociotechnical production system; to determine the nature of the variance; determine the extent to which the variance is controlled; and to determine the extent to which tasks should be taken into account in redesign of operating roles in the supporting subsystem units.

According to the Clegg et al. (1989) method of function allocation, individual and cumulative allocations made on a provisional basis earlier can be further evaluated against requirements specifications (including the scenarios developed earlier); resources available at the time of implementation (including human and financial); and the sum total outcome. In addition to a check of function allocation, interfaces among subsystems should be checked and redesigned at this juncture.

Especially at the team and individual levels of work, the internal physical environment should be ergonomically adjusted if necessary to promote human well being, safety, and effectiveness. Evaluating the technical and personnel variance analyses, we can assess whether there are physical environmental changes that will promote improvement. These changes might include changes to temperature, lighting, humidity, noise control and hearing protection, and so forth.

2.11. Implement, Iterate, and Improve

At this point, it is desired to execute or implement the work process changes prescribed, design interfaces, and allocate functions. As in most cases, the macroergonomics team will not have the authority to implement the changes suggested by the analysis, proposals with recommendations for change may be required for presentation within the formal organizational structure. Such proposals should be consistent with the macroergonomic principles and should include, for example, both technical and social objectives, will likely include participatory ergonomics and should predict multidimensional performance improvement. Based on the proposal feedback, modifications to the proposal may be necessitated, which will require a return to the earlier step that represents a challenged assumption or design.

This process is iterative. For continuous improvement (i.e., STS principle of "incompletion"), evaluations may suggest a return to an earlier step in the process for renewed partial or full redesign. Once the proposal for change is accepted and implementation begins, regular reviews of progress are required. To compliment the weekly formative evaluations performed by the implementation team, semi-annual formative evaluations should be performed by an objective outside party. This evaluation should be presented to the implementation team and a constructive dialogue about expectations and progress-to-date should be conducted.

3. CASE VALIDATION

3.1. Measuring Safety and Quality

As illustrated in Figure 2, Sink and Tuttle (1989) suggested organizational performance can be measured or assessed using seven performance criteria or clusters of measures: efficiency, effectiveness, productivity, quality, quality of worklife, innovation, and profitability or budgetability. The seven performance criteria relate to specific parts of the organization as represented by an input-output model similar to that proposed by Deming (1986). Within a given performance criterion, specific measures can be derived. Data sources for each measure can be subjective, as in the case of self reports, or can be based on objective data. Kleiner (1997) contributed a flexibility criterion that related to each of these checkpoints as well, due to the increasing need to manage and measure flexibility in systems. According to Sink and Tuttle (1989), quality of work life (QWL) includes safety as a criterion, however, it is proposed to differentiate the need for a healthy and safe working environment from QWL, the affective perception of the total work environment. The efficiency criterion focuses on input or resource utilization. Effectiveness focuses on whether objectives are realized. Productivity is operationalized as outputs divided by inputs. Innovation refers to creative changes to process or product, which result in performance gains. Profitability is a standard business management criterion. For non-for-profit organizations, Sink and Tuttle (1989) introduced budgetability or expenditures relative to budget to replace the profitability criterion. Quality Checkpoints 2 and 4 correspond to traditional measures of quality control, traditionally assured through inspection of inputs and outputs respectively. Quality Checkpoints 1, 3, and 5 are quality criteria popularized by Deming and the TQM movement. In essence, a TQM approach to quality moves resources from Checkpoints 2 and 4 exclusively to share resources with at the other system checkpoints. Checkpoint 1 emphasizes the quality of suppliers, which has been operationalized within the quality movement in the form of supplier certification programs and processes. Checkpoint 3, in-process control, pertains to the use of statistical quality control charts to monitor and control processes. Checkpoint 5 refers to customer satisfaction, operationalized as the customer getting what is wanted and needed. Checkpoint 6 corresponds to total quality management or the method by which the other criteria are managed.

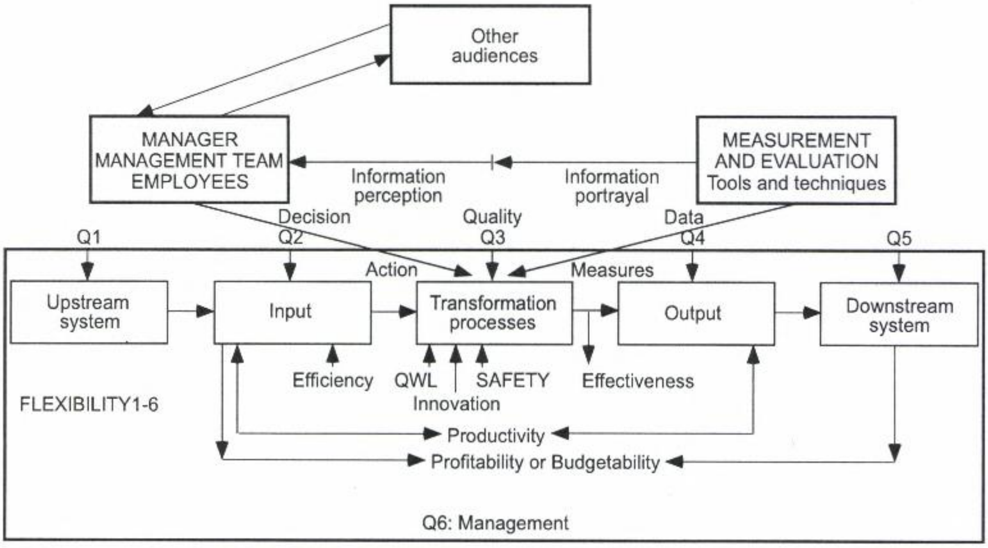

Figure 2. Performance criteria in a work system. *Notes.* Adapted from Sink and Tuttle (1989). QWL—Quality of Work Life, Q—Quality Checkpoint.

3.2. Case 1: Development of a Safety Culture

3.2.1. Analysis

Perhaps there is no greater change in an organization's life than a fundamental change in purpose. In the United States, the nation's former nuclear production facilities and sites were operated by management and operations (M & O) contractors. In the 1980s, due to the end of the cold war and other factors, there was a shift in focus from nuclear production to provide leadership in the environmental restoration arena.

At a large nuclear site, safety was a major concern as the environmental restoration mission unfolded. The objective was to transform the culture from a "production-oriented" culture to a "safety" culture. The construct of safety culture is defined in INSAG-4 (International Atomic Energy Agency, 1991) as "safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance."

Given that most of the facilities were constructed in the period around World War II, safety, both nuclear and industrial, was viewed as a vital concern as nuclear and other hazardous materials were cleaned up.

Before embarking on an intervention to improve safety in general and to improve the safety culture in particular of one such installation, a system scan and environmental scan were developed. The type of information obtained appears in Table 2. As can be seen, consistent with a sociotechnical systems approach, variances were the focus. Several variances were noted between the current state and the desired (i.e., future) state.

A survey instrument was also designed by consultants to collect data about organizational climate. As a follow up to this survey, the author

TABLE 2. System and Environmental Scan

Item	Current	Desired
Purpose	Produce products for national security and make a profit for company	Be the nation's model for restoration of land systems and application of advanced restoration technologies
Philosophy	• Management controls • Do what it takes to get throughput	• Emphasize quality and safety
OBJECTIVES		
Technical	Make a profit, maintain contract with customer, reduce costs	• Restore the environment for profitable use (education, agriculture, businesses) • Comply with environmental regulations • Develop marketable environmental technologies
Social	Avoid strikes with union or stockpile products to avoid supply interruption	• Develop cooperation among employees and with external stakeholders • High levels of quality and safety
Outputs	Weapons-grade materials, products	• Environmental restoration expertise • Reservation environment safe for profitable or recreational use
Inputs	Unprocessed materials, product components, other raw materials	• Contaminated environment • People willing to work and learn
BOUNDARIES		
Throughput	Suppliers, products ready for shipping are at the boundaries	Input: government regulations; Output: knowledge base in libraries

TABLE 2. (cont.) System and Environmental Scan

Item	Current	Desired
Territorial	Nuclear complex	Nuclear complex and nearby schools doing training
Social	Company production employees are in the system	Researchers supplying knowledge, contractors, customer and state become part of the work system
Time	Fiscal year budget contract period	20-year contract period
EXPECTATIONS		
Union-to-system	Abide by contract	Work together to increase capabilities, safety and contributions of employees and their families
System	Do not interrupt work, give concessions	
News media	Give information for big story	Give us a shot at good stories
System	Do not make us look bad	Help change our image, publicity
State	Abide by regulations, keep honest records	Joint: showcase what can be done through cooperation, publicity
System	Cut us some slack to make products	
Customer	Products whenever needed	No political embarrassment
System	Profit, jobs, contract	Contract, profit, showcase
Local community	Jobs, pride in community	Jobs, pride in reclamation, safety
System	Labor force, no hassles	Labor force, cooperation
Presenting Problems	• Lack of cooperation and relationships with internal and external environment • Management needs to develop consistency between espoused vision and values and what it does • Workforce may lack skills and desire to pursue clean-up • Lack of knowledge about what's in the ground or tanks • Lack of knowledge about how to clean up environmental hazards	
Future Scenario	Realistic: site closes, someone else comes to clean up, we get lawsuits for contamination, stock value depresses	Idealistic: get new contract, become showcase on how to clean up resulting in new contracts elsewhere, favorable impact on stock value

Notes. Adapted from Groesbeck, Sienknecht, and Merida (1998, with permission).

conducted an assessment, which focused on identifying variances between key programs, processes, and practices that should be improved to achieve substantive changes in safety behavior.

3.2.2. Design

Following the analysis phase partially described, systematic alignment of programs and processes with the new safety values was pursued. In many cases, existing programs rewarded behavior or performance that could be perceived as trading off against safety. For example, rewarding on-time attendance or productivity could adversely affect safety. Variances were identified, and roles were identified to investigate how key personnel could be assisted to control variances more effectively in the future. In many cases, there was a training solution; in other cases, technical solutions such as providing information-based support was needed. Another technical focus was on improving lock and tag processes.

Concurrently, top management and the communications department were mentored regarding their perception of their roles versus what was expected of them. Help was given in communicating and reinforcing a fundamental paradigm shift with respect to core values. The analysis had revealed that rather than adopt an ergonomic perspective of safety, that is, to assume accidents were the result of a human-system mismatch, the company was sending signals that operator error was generally the cause of accidents. Rather than focus blame upon workers, it was desirable to focus on changing the system with training supporting the change process. Interventions included all hands meetings, labor relations, internal, and external communications, reward program changes, and participatory planning. The latter was highlighted by a "strategic summit," where the top leaders from the government and the four independent site contractor organizations worked through a participatory process of site evaluation, planning, and management.

3.2.3. Results

At this site, a safety culture was developed in approximately one year, where culture change is normally expected to take five or more years. The change was attributed to a combination of top management leadership and closing the gap between current and desired culture by attending to social and technical subsystem deficiencies (i.e., joint optimization) and organizational redesign. The objective measure of success was the customer's financial reward for performance improvement called an award fee. This was available for the management and operations (M & O) contractor to earn each year based on performance. The new safety culture was attributed by the customer as the major reason for a significant M & O award fee.

3.3. Case 2: Improving Health and Quality in Tire Manufacturing

3.3.1. Analysis

The manufacturing facility described was one of two plants operated by a global tire manufacturing company in the USA. The facility described was located in the Northeast. An analysis was performed during the environmental scanning phase.

Figure 3 illustrates the identification of unit operations or STS groupings and associated technical processes.

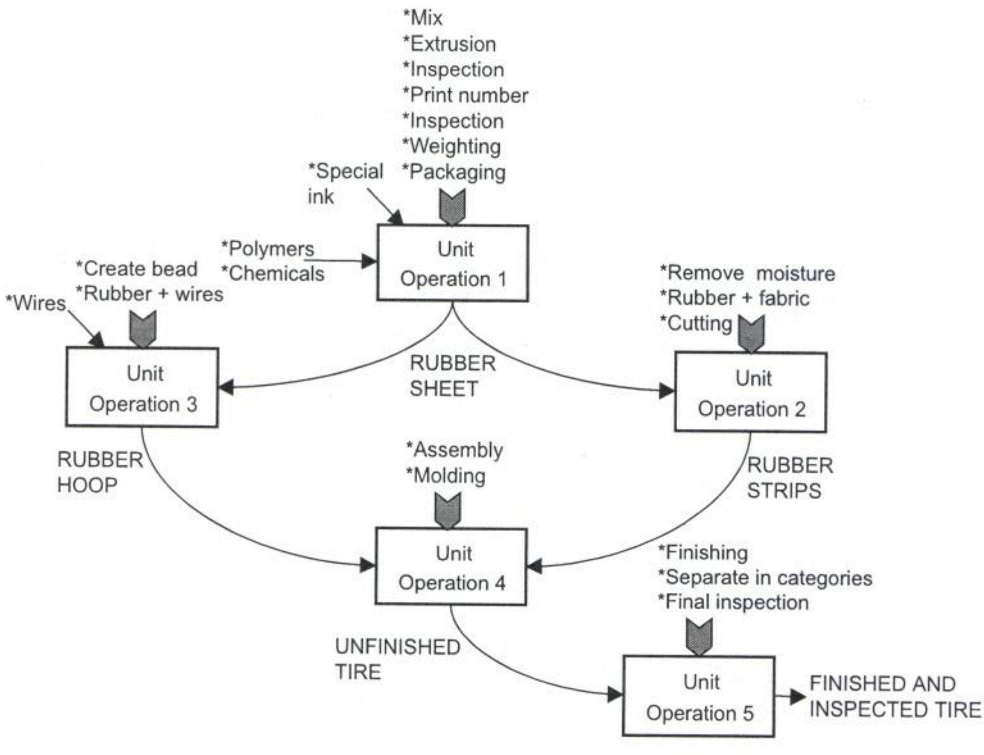

Figure 3. Unit operations in tire manufacturing. *Notes.* Adapted from Blanco and Duggar (1998, with permission); A, B—other subprocesses.

Figure 4 illustrates some of the technical production processes seen in tire manufacturing.

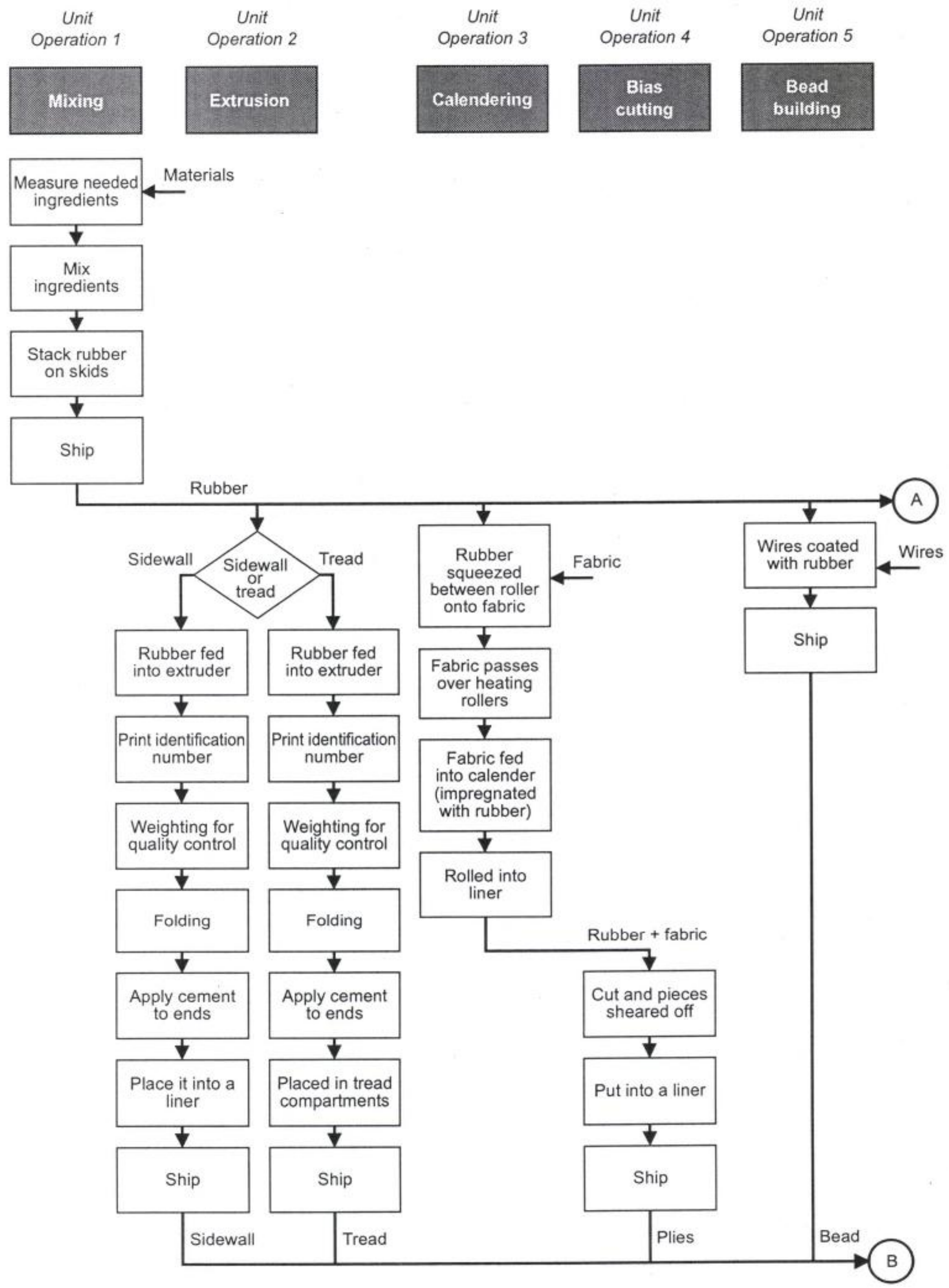

Figure 4. Technical processes in tire manufacturing. *Notes.* Adapted from Blanco and Duggar (1998, with permission).

As previously stated, key variances have a significant impact as a single variance, especially related to safety, quality, schedule, or cost, or they interact with other variances to have an effect on several other variances. For the tire manufacturer, based on the variance matrix in Table 1, we identified key variances. The types of variances discovered in this procedure are illustrated in Table 3.

TABLE 3. Identification of Key Variances in Tire Manufacturing

		Type of Key Variance		
Key Variance	Unit Operation	Significant Downstream Impact	Numerous Relationships with Other Variances	Significant Impact as a Single Variance
Raw material consistency	Mixing	✓	✓	✓
Raw material composition	Mixing	✓	✓	✓
Mixing duration	Mixing	✓	✓	✓
Rubber quality	Tread Extrusion	✓	✓	✓
Tread thickness	Tread Folding	✓	✓	
Adhesive strength	Tread Cementing	✓	✓	
Quantity adhesive used	Tread Cementing	✓	✓	
Rubber to fabric adhesion	Rubber Impregnation	✓	✓	✓
Bond consistency	Rubber Impregnation	✓	✓	
Wire to rubber adhesion	Bead Building	✓	✓	✓
Bond consistency	Bead Building	✓	✓	
Wire surface quality	Bead Building	✓	✓	
Wire to rubber adhesion	Wire Enveloping	✓	✓	✓
Component dimensions	First Stage Building	✓	✓	✓
Press force	First Stage Building	✓	✓	✓
Press duration	First Stage Building	✓	✓	✓

Notes. Adapted Groesbeck, Sienknecht, and Merida (1998, with permission).

A key variance control table is illustrated in Table 4 to demonstrate the types of data collected for key variances in order to better support the focal roles.

3.3.2. Design

As a result of the formative analysis, a major program to improve quality and safety based on the sociotechnical approach was developed. This program consisted of a knowledge and skills based training program coined Training and Education for Advanced Manufacturing

TABLE 4. A Variance Control Table for Tire Manufacturing

Key Variance	Unit Operation: Where Occurs	Unit Operation: Where Observed	Unit Operation: Where Controlled	Controlling Role	Controlling Action	Information Needed
4: Width of Rubber Strip	Unit Operation 2: Extrusion	Unit Operation 2 or 7: Extrusion	Unit Operation 2: Extrusion	* Machine mainten-ance	* Machine adjustments	* Reports from machine operators and quality inspectors
				* Machine operator	* Machine adjustments or call maintenance	* Visual inspection acceptance standards, product observation
				* Quality inspectors	* Stop production or reject failed products	* Weight of product, weight standard
6: Weight of Rubber Strip	Unit Operation 2: Extrusion	Unit Operation 2 or 7: Extrusion	Unit Operation 2: Extrusion	* Machine mainten-ance	* Machine adjustments	* Reports from machine operators and quality inspectors
				* Machine operator	* Machine adjustments or call maintenance personnel	* Visual inspection acceptance standards, product observation
				* Quality inspectors	* Stop production or reject failed products	* Weight of product, weight standard
7: Amount of Cement Applied	Unit Operation 2: Extrusion	Unit Operation 2 or 7: Extrusion	Unit Operation 2 or 7: Extrusion or Tire Building	* Machine mainten-ance	* Machine adjustments	* Reports from machine operators and quality inspectors
				* Machine operator	* Machine adjustments or call maintenance personnel	* Visual inspection acceptance standards, product observation
				* Quality inspectors	* Stop production or reject failed products	* Visual inspection to determine if cement is holding

TABLE 4. (cont.) A Variance Control Table for Tire Manufacturing

Key Variance	Unit Operation: Where Occurs	Unit Operation: Where Observed	Unit Operation: Where Controlled	Controlling Role	Controlling Action	Information Needed
8: Quality of Fabric	Unit Operation 3: Calendering	Unit Operation 3 or 7: Calendering or Tire	Unit Operation 3: Calendering	* Incoming-quality inspector	* Reject batches of inferior quality and call supplier	* Product observation, measurements, acceptance standards, and incoming-product supplier certification
				* Machine operator	* Call incoming-quality inspector	* Visual observation and acceptance standards
26: Shape after Molding	Unit Operation 8: Curing	Unit Operation 8 or 9: Curing or Finishing	Unit Operation 8 or 9: Curing or Finishing	* Machine maintenance	* Machine adjustments	* Reports from machine operators and quality inspectors
				* Machine operator	* Machine adjustments or call maintenance	* Visual inspection acceptance standards, product observation
				* Quality inspectors	* Stop production or reject failed products	* Product observation, results from roundness and balance inspection, and acceptance standards

Notes. Adapted from Blanco and Duggar (1998, with permission).

(TEAM) and micorergonomic intervention focused on the reduction of lifting and twisting injuries and accidents. The TEAM program was a multimedia approach to education, training, and development. Instructional videos were produced as were training manuals. This involved identifying unit operations and operating roles. The emphasis was on educating users about the underlying knowledge and theory behind skills. Once variances were identified, troubleshooting guides were designed to control process variances. Rather than simply instruct operators on *what* to do when a certain event occurs, information detailed *why* a certain action solved the particular problem. These were placed at the point of variance control, that is, the operators' workstations, as suggested by the STS principle of "power and authority" (Taylor & Felton, 1993). This approach to variance control specifically addressed the need to improve product quality, and focused on the in-process quality checkpoint. The micoergonomics program focused on system redesign to reduce back injuries. Again, variances, in this case, variances that exceeded human capability and limitation were the focus.

3.3.3. Results

As was stated at the outset, the forces from the environment will ultimately determine the work system's success. As is the case with many plants, a major change in the environment occurred and was announced during the sociotechnical analysis process. It was announced the corporation was taken over by a major foreign conglomerate. The new international owners reported the TEAM program was an integral part to comprehensive approach to quality and safety improvement and was a good umbrella for their approach to TQM.

Another environmental issue surfaced when the corporation announced it would search for the ideal locale for a state-of-the-art medium truck radial facility. It was widely assumed if the local region were not selected, regional operations would be discontinued. The ergonomics work within this plant was attributed by its Chief Executive Officer as a significant factor in the corporation's decision to locate its new state-of-the-art manufacturing facility in the region, resulting in hundreds of new jobs (and retaining hundreds of existing jobs). Finally, as an objective outside evaluation, a national organization awarded this program their prestigious Project-of-the-Year Award, based upon significant performance improvement. The project also culminated in both operational and economic development results (see Table 5).

TABLE 5. Tire Plant Results and Economic Development Outcomes

Organizational Results	Economic Development Results
National Project-of-the-Year Award	900 jobs retained
Reduced lost time injuries	U.S. $100 million facilities expansion
3-month return on investment (ROI)	250 jobs created
Improved communication and teamwork	
Improved product quality	

4. CONCLUSION

Taking a macroergonomic approach has been contended to benefit safety and quality performance (Hendrick, 1997). Macroergonomics can integrate the concepts, methods and tools of ergonomics, TQM, and STS. For the ergonomist, the macroergonomics perspective leads to more significant results. For the TQM practitioner, STS, the theoretical base for macroergonomics, provides a needed "umbrella" theory. In terms of the relationship between TQM and ergonomics, TQM offers the ergonomist several practical tools. Similarly, the ergonomist offers TQM tools and techniques at both the macroergonomic and task levels of improvement. The benefits of the macroergonomic approach have been demonstrated here and in other literature at the factory level in terms of 50–100% quality improvement (e.g., Kleiner & Drury, in press) as well as at the community level, where economic outcome improvements as measured by job retention or expansion have been demonstrated. This article contributed a specific methodology for conducting macroergonomic analysis and design in the interest of improving safety and quality performance.

It is hypothesized the dramatic results achieved at the tire plant were due to the ergonomists initially and continuously managing the interface between the environment and other subsystems, viewing the environment as a source of inspiration rather than provocation (Pasmore, 1988) and integrating social and technical interventions jointly. The environmental subsystem consisted of such components as political, legal, and educational stakeholders. By working directly with state officials and institutions, organized labor, and corporate headquarters, intervention focused on the political interface with local organizations when takeovers and the like were announced. By transferring knowledge acquired during environmental system analyses, educational programs and ergonomics interventions were designed and implemented.

Similarly, at the nuclear site, a change in safety culture began with a valid understanding of the environment and a systematic formative evaluation of the current system. Only then could reliable and valid design interventions be constructed and implemented. By understanding the causal forces from the environment, changes to the personnel subsystem and technological subsystem could be jointly designed, resulting in improved perceived and objective safety performance. Whereas case studies help to make the case, more rigorous formative and summative research is needed to refine and validate the proposed methodology respectively.

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