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Keywords: production system design; human-systems integration; networks; participatory process; team; biotechnology

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Overcoming Production Disruption When Adopting New Technologies: Application of Macroergonomics and Safety Culture

Abstract

Organizations are continually responding to advances in technology in order to remain competitive. Depending on the nature of the technology, incremental changes to the workflow may be adequate. However, at some point, the technical demands may be disruptive because the organization is unable to properly adapt. In this case study of a biotechnology production facility, rapidly changing customer and technological demands, as well as the lack of systems integration, created a disruption that manifested in rising employee injuries and production interruptions. The disruption was ultimately addressed through a comprehensive redesign of human-system relationships. Key elements included: a management team willing to examine the entire production system; a multidisciplinary team coordinating efforts toward a common goal; staff engagement; and building feedback channels to guide the actions of supervisors and managers. The methods used in this successful case study, involving a Macroergonomics approach, may be applied to any private or public enterprise.

Keywords: production system design; human-systems integration; networks; participatory process; team; biotechnology

Introduction

Today's organizations are confronted with disruptions to their overall effectiveness from rapidly changing technologies, greater customer expectations, global competition, and added costs. In addition to profitability and efficiency, organizational effectiveness is also measured by the ability to produce outputs reliably, safely and sustainably. These longer-term concerns are rooted, in part, in corporate social responsibility, sustainability, and current societal value systems.

While organizations may understand the need for change in response to technology, they are challenged by the simultaneous demands to maintain current operations while adapting to new technologies. It is far easier to defer change until a disruption is imminent. Maintaining worker engagement and health are critical in achieving production and quality goals. This is a case study of a biotechnology production facility that during a rapid increase in production demands experienced increased staff injuries and increasing production interruptions that were ultimately addressed through a comprehensive redesign of human-system relationships using a Macroergonomics approach.

Traditional Responses to Technology and Change

Typical attempts to respond to technology changes mirror the organizations that created them. Organizations operating in technologically complex environments tend to be highly differentiated, which creates integration challenges (Lawrence and Lorsch, 1967). This differentiation can lead to one-dimensional or narrowly focused responses and, not surprisingly, unintended consequences. Moreover, highly differentiated organizations tend to rely heavily on technical experts, specific technologies, or disciplines that work independently with poor coordination among departments.

Hierarchical organizations typically act using top-down approaches as a normal and necessary way of responding to changes. It is an efficient and natural part of organizational culture. However, it may not be the most effective way of dealing with complex, technologically initiated changes involving extensive adaptation in human interaction and behavior.

These expert-driven, top-down responses to an organizational problem do have appeal because they are focused, action-oriented, and, on a superficial level, seem to have credibility to solve the problem at hand. This creates a sense of comfort and confidence in the organization that the problems have been identified and a solution is imminent.

A Systems Approach for Responding to Technology and Change

Since the 1960's, many observers of public and private organizations have critiqued the traditional response and the organizations that created them. Once the organization and its actions are viewed in a systems context, it is easier to understand the unintended consequences of their actions. This systems view, made popular by writers such as Katz and Kahn (1966), Senge (1990), and Checkland (1981), recognizes that organizational outputs results from a complex throughput process that transforms inputs from the environment. These input-throughput-output relationships require organizational feedback loops that are essential to understand in order to create appropriate actions.

Macroergonomics

Developments in ergonomics have mirrored this kind of systems thinking. First, the definition of the ergonomics discipline itself focuses on the system: Ergonomics (or Human Factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance. (Dul, et al 2012). Ergonomics/Human Factors is necessarily about the system, not isolated elements viewed separately/independently. It requires planning and design to simultaneously consider overall system effectiveness and human well-being. The discipline of ergonomics brings methodologies, analyses and solutions that can help address both human and organizational needs. Managers often perceive ergonomics as focusing on occupational health and safety and related issues, not organizational performance (Dul and Neumann, 2009). However, in addition to this concern regarding physical risk factors for work-related musculoskeletal problems, ergonomics looks at the cognitive and other demands of the job, which can affect error rates and productivity.

As ergonomics evolved, the scope has broadened from a limited focus on problems with narrow physical and cognitive sources to more complex organizational contexts (Hendrick 1984, 1986). This latter approach, called Macroergonomics, acknowledges the importance of human factors in diagnosing problems and making system improvements. Macroergonomics requires that we attend to the technical, organizational and human dimensions that impact our efforts to create adaptive human and organizational responses to change.

Human Systems Integration (HSI)

At the same time, governmental bodies and business observers began to realize the value of this systems approach. Human Systems Integration (HSI) has gained traction and is recognized as an important approach to view systems (NASA, 2015). This perspective has been a major enabler in implementing change and creating sustainable technological innovation (Durso, et al) and is represented in the US National Academies of Sciences, Engineering, and Medicine by the Board on Human-Systems Integration (BOHSI, 2016).

The systems approach, Macroergonomics, and Human-Systems Integration offer principles and methods to implement change in organizations that experience rapid changes in technological environments. This approach is consistent with previous thinking on the causal pathways to worker injuries (NRC/IOM, 2001). In this conceptual model, worker injuries are the result of two broad classes of variables: personal factors, which include individual abilities and limitations, and the physical and cognitive demands of the workplace, the organization, and the social context within which the activity occurs. This model suggests that organizations seeking to make real changes to improve their overall effectiveness and competitiveness, and reduce injury risks, must use a broader systems approach.

To date, few studies have documented the effectiveness of the systems approach in practice. Organizational field research is difficult to control and eludes rigorous research designs. Occasionally, there are events and circumstances that provide insight into the change process in organizations and an opportunity to document these effects. This paper describes one such case.

Case Study: The U.S. Department of Energy Joint Genome Institute

This organization presents a useful case study because the rate of technology change accelerated over a short period of time. Rapid innovations in DNA sequencing technologies created high demands very quickly. This led to a production disruption, an intervention, an adaptation, and ultimately a new stability. During the early period of this case study, from 1997 to 2005, production output increased from 0.1 to 3.1 billion bases analyzed per month (Figure 01). This increase was driven by demand and a reduction in cost through the rapid adoption of advanced sequencing machines.

Establishment of the Organization

The US Department of Energy Joint Genome Institute (JGI) is a federally funded high throughput genome sequencing and analysis facility that was established in 1997. JGI employs approximately 280 technicians, scientists, analysts, engineers, and operations support staff.

DNA sequencing is the process of determining the precise order of nucleotides within a DNA molecule. “Just as computer software is rendered in long strings of 0s and 1s, DNA, the ‘software of life’, is represented by a string of four chemicals, abbreviated as A, T, C, and G. To understand the software of either a computer or a living organism, we must know the order, or sequence of these informative bits” (JGI, 2006). The JGI provides high-throughput DNA sequencing and computational analysis for research scientists and institutions around the world. JGI ‘products’ are very large, detailed files of genetic information of organisms in a format that can be used to understand the properties and functions of existing living organisms. When the JGI was established in 1997, it focused on sequencing human chromosomes as part of an international collaborative effort called the

Human Genome Project. After 2003, when the Human Genome Project was completed, the JGI became one of the US Department of Energy's national user facility and focused on large scale sequencing of DNA of other organisms, such as microbes, fungi and plants for their potential impact in providing solutions to energy and environmental challenges, key missions of the U.S. Department of Energy.

The JGI's facility was a mix of office and laboratory environments that included research and production work. Production line staff, which increased to approximately 65 technicians in this time period, worked across three shifts, 24 hours per day seven days a week. The technicians performed various manual tasks, including sample handling in the laboratory, and data management in the office. This hand intensive work included sample tracking and storage, repetitive pipetting, data input and sample plate handling tasks (Figures 02 and 03).

Samples progressed through the production process through ten work centers. Each work center required manual steps to prepare and handle samples for semi-automated equipment. The production process was customized, based on the customer needs. In 2002, JGI's customer base was relatively small, with only 225 customers and approximately 60 genome projects. Ultimately, the JGI mission expanded to thousands of genome projects for over 17,000 customers.

As the JGI evolved into a large-scale production facility, with the adoption of new more productive sequencing technologies, the throughput and the number of customers serviced dramatically increased. JGI managers and engineers brought in sophisticated equipment, creating 'islands of automation' connected with many manual steps. By 2005, JGI was running 106 of the most advanced sequencing machines available involving 5 different sequencing technologies. The new semi-automated machines were rapidly inserted into production lines, but they required the manual tracking, preparation and transfers of thousands of sample plates into and out of semi-automated equipment. This increased hand intensive work that was required to support and link the new machinery to the production process. The tasks of preparing, loading, and unloading samples in small plastic 96-well plates required a high level of precision in manual handling the samples, which increased the risk of injury (Christensen, 2003).

In addition, requirements for quality of submitted samples were not strictly enforced. Samples were submitted without the mass, volume, and concentration guidelines established by JGI, resulting in failures from poor quality. This created re-work and reduced morale. Management was primarily focused on the production throughput metrics and were not as effective in evaluating the related human workload and inefficient manual work processes.

Another contributing factor was that technicians, who were highly trained and motivated, many with graduate degrees, often rushed through their primary production tasks in order to gain time to perform special sequencing activities. These special activities were projects offered to technicians on a voluntary basis, and were more interesting than the usual production tasks. This additional work was poorly coordinated with the overall workload, and had the effect of adding untracked physical demands for the hands and arms.

2007: The Disruption: A Tipping Point

By late 2007, the increased manual workload associated with accommodating new technologies and increased throughput disrupted production. Rising production demands led to increased high precision work and a high rate of hand and arm musculoskeletal fatigue and injuries that impacted up to 9% of the workforce. These reported injuries represented the tip of the iceberg: it was later determined from a confidential survey that 75% of production technicians had musculoskeletal discomfort.

Ergonomics consultants had been called in at various times, but their analyses and recommendations focused on the specific tasks that appeared to be most problematic. Management failed to recognize the ongoing system-level problems that were accumulating with the rapid adoption of each new technology. The growing physical demands on staff and a technology adoption process that did not consider the physical demands on staff led to inefficient work processes, staff injuries and declining worker morale and confidence in management.

Examples of workflow disruption included placement of new equipment in locations that did not match production flow and made them difficult to access and use (Figure 08). The new technologies also increased the use of computer keyboards, often without any planning for their location or consideration of hand positions needed to use them.

Employee morale was undermined on several occasions when technicians arrived at work after a weekend off and found their workplace reorganized without any consultation. Production technicians were not involved in planning for production process changes. The changes often led to reduced efficiency of sample processing.

Some of the work teams were small, with 6 employees or less. When an injured technician was off work or their work was limited to tasks that were not hand intensive, the workloads of the remaining employees increased. Employees were moved to different areas of production to perform the work of injured employees, resulting in bottlenecks, increased error rates, and reductions in overall production.

December 2007: The Macroergonomic Intervention

In an unprecedented action, all production was halted for the month of December 2007. Known as the “Production Stand Down”, the JGI Director and his management team took this dramatic action to create a comprehensive opportunity to improve the safety culture. A consultant with a focus on Macroergonomics (Imada) was brought in to identify and address the systems issues that were at the heart of the disruption. Management initiated a participatory process, using small interdisciplinary groups, to evaluate all standard operating procedures. This was a bottom-to-top, month-long participatory process to address all systems issues that needed improvement.

Employee engagement

Production line and engineering management reached out to technicians for assistance in solving the issues associated with recurring injuries and production disruption. Employees are often well positioned to provide practical and executable solutions to production problems, since they are the most familiar with the work process and have often thought about work improvements. An employee-driven Safety Culture Working Group was formed consisting of employee representatives from various departments, including Environmental Health and Safety (EHS) specialists and engineers. The JGI Safety Culture Working Group provided a forum for anonymous reporting of issues and concerns, provided rewards and recognition ideas for improvement, distributed safety information, and hosted weekly events to promote ergonomics and safety.

Employee engagement was evident in a team approach to establish production process improvements, improve equipment and tool selection, and establish best practices and priorities for change. All staff received basic training in the identification of risk factors for work-related musculoskeletal disorders and were provided with examples of job improvements to reduce risk. Improvement priorities were based on criteria such as production throughput, quality, risk of injury, cognitive demands, feasibility, timelines, and costs. Everyone had a “seat at the table”, and line employees were instrumental in testing, evaluating and providing recommendations for changes.

Production Process Changes

Several process changes were made to increase involvement of supervisors and line management with safety issues, including improving work planning and early identification of potential safety issues. In small groups, employees assessed physical risk factors and fatigue levels for each task and these were used to prioritize task rotation and task redesign. This assessment by employees allowed supervisors, for the first time, to better plan a mix of work tasks and job rotation. Supervisors and workers collaborated on trying various combinations of tasks and durations of tasks for optimal productivity and safety planning.

JGI staff identified that the layout and workflow of the production area were contributing to the high amount of production line failures. Workflow “spaghetti” diagrams were created to follow the way samples moved throughout production. This is commonly used in Lean initiatives, process management and improvement methods that focus on reducing waste in a process. The work flow diagrams provided insights and clues to identify where bottlenecks on the production line were occurring, and how to restructure the layout of the production areas. Improvement to the layout and workflow aided in speeding up the turnaround time of samples, reducing the failure rate, and in improving work safety by eliminating unnecessary movement.

Some work areas did not have clear protocols for task performance. Step-by-step protocols were developed during the stand down that not only included specific information about how tasks should be performed but also how best practices for lower risk and better ergonomics could be followed. Since some of the process steps were time sensitive, and the samples could degrade, the protocols even included instructions such as “Place sample on ice and take a 5 minute break” when the upcoming steps in the process were highly repetitive or when processes would be negatively impacted by human error or fatigue. This reinforced the message that the science and production demands of the task were linked to employee safety and fatigue.

Another process change was to create a more formal supervisor walk-around process. On a quarterly basis, supervisors were required to walk around each assigned work area and meet with employees to complete a checklist to identify various safety hazards. The supervisor walk around helped supervisors connect with employees, demonstrated a commitment to safety, allowed direct communication with employees, and proactively addressed potential safety issues.

Since the equipment and technology were frequently updated, a change review process was established that began prior to the introduction of a new technology in the production process. A formal sign off process was created for safety and ergonomics staff to raise concerns, during pilot testing of a new technology, regarding impacts the changes might have on worker safety or productivity.

Job Enlargement and Job Rotation

Job enlargement involves the redesign of work to increase the variability of both physical and cognitive demands of a job. An example is at the Ducati motorcycle production line in Modena, Italy, where 2 employees assemble a whole motorcycle themselves rather than performing the same task on all the motorcycles. In contrast, job rotation could involve workers performing the same repetitive actions but rotating between repetitive tasks every 2 to 4 hours. With job rotation, if the tasks are similar enough, there is little variation in physical or cognitive task demands.

At JGI, the addition of job enlargement and job rotation, enforcement of work hours and breaks, and role clarification all contributed to a reduction in injury risk and improved work efficiency. Effective job rotation necessitated cross-training of the technicians so that they could perform a wider variety of roles on the production line. The training included not only the protocols and procedures required to perform the tasks, but also best practices for performing the specific tasks safely and with improved ergonomics. Job enlargement allowed greater flexibility to meet the staffing needs. After the Production Stand Down at JGI, both job enlargement and job rotation exposed employees to different tasks with different physical demands. Task requirements of the each job were taken into account to balance the physical demands of work across employees and across the day of work. For example, high precision tasks, such as pipetting, were identified and spread out among employees. Likewise, job rotation allowed for the variation of cognitive demands across the day so that more repetitive and tedious tasks could be alternated with those involving a higher level of problem solving. Tedious and mundane tasks can lead to higher error rates since employees may switch to an “autopilot” mode of work and, through lack of attention, may make mistakes. Tasks involving high cognitive demands, decision-making and problem solving may also result in errors if performed for long periods of time, since employees may become mentally fatigued.

Job enlargement and rotation also created a workforce that was more flexible and able to adapt to the changing needs of production. Prior to the Production Stand Down, technicians were specialized and covered specific roles in production. This led to periodic backlogs, suspension of production, and the need to schedule overtime or weekend work. Cross training enabled supervisors to have more staffing options to cover different parts of the production process as needed, reducing the higher wage costs associated with overtime and weekend pay.

Another concern was that there had been confusion among employees as to who was responsible for coordinating scheduling and staffing -- employees would receive directions about daily assignments from more than one person. Production, Research and Development (R&D), and Quality Assurance (QA) tasks were poorly coordinated and prioritized. As a result, there were times when tasks were not completed because employees would be focused on other tasks provided by different staff members. The new role of 'shift leads' was implemented to ensure that all work in Production, R&D and QA was coordinated and prioritized by a single person.

Examples of Workstation, Tool and Equipment Redesign

During and after the Production Stand Down, there was a strong and committed focus on improving the organization’s safety culture; a multi-pronged approach of many micro-organizational changes were implemented. Prior to the stand down, production capacity and throughput planning often only considered the limits of machines. After the stand down, the organization considered the safe limits for manual processes performed by employees, and identified unnecessary re-work, bottlenecks in production, equipment maintenance and repairs, and troubleshooting. Tasks, tools and workstations were modified based on worker feedback and input from ergonomics and engineering staff.

The review identified inappropriate work surface heights for manual tasks leading to wasted motions and increased back and neck fatigue (Figures 9 and 10). As a result, easily adjustable electric height work surfaces were installed at many workstations.

Custom laboratory counters and biosafety cabinets were developed through a feedback process with employees, supervisors, ergonomists, and engineers to improve the efficiency of work and reduce reach distances and awkward arm and hand positions (Figure 11). Prototype designs were developed with cutouts to place frequently accessed items at a comfortable, efficient location, and with a 'body pocket' to allow technicians to position themselves close to their work. The designs were substantially improved with practical feedback from employees who tested the designs, performing realistic tasks at the prototypes (Figure 12). A final workstation design was built based on the participatory design process (Figure 13).

Large 23 x 23 cm culture cell plates were frequently used to grow millions of bacteria colonies by spreading growth media onto the plate with glass beads. The processing required the manual handling of multiple plates (3 kg), using a wide pinch grip, to hold and repeatedly shake the plates for 100 shakes per minute, over the course of an hour (Figures 14-15). Technicians and engineers developed a “Shake N Plate” device to eliminate prolonged gripping of the plates so that the technicians could easily pivot and rotate a stack of plates using handles and this device was later motorized by the JGI engineering group (Figure 15).

Many more problem tasks were identified by technicians, who worked together with supervisors, ergonomists and engineers to design new tools or modified processes that were successfully implemented in the production lines. The JGI interventions were demonstrated at several annual Applied Ergonomics Conferences (sponsored by the U.S. Institute of Industrial and Systems Engineers) and in 2007 and 2010 received the coveted Ergo Cup® successfully competing against large multinational corporations, thereby boosting staff morale.

Smaller plates with 96 or 384 wells were used throughout the production process. These plates were sealed with aluminum foil and placed in freezers for later processing. The force required to pull off the aluminum foil was nearly the maximum pinch strength of the technicians and was identified as a high-risk task (Figure 16). A custom machine was designed and built to mechanically remove the foil, significantly reducing the injury risk for this task (Figure 17). Ultimately, it was determined that the process of freezing and thawing the samples was increasing failure rates and led to contamination of samples from the glue residue from the foil seal. The workflow was changed to allow the samples to continuously flow through the production line with less use of foil seals and placement into freezers. Foil seals were replaced with seals that did not contaminate samples and could be applied and removed by mechanical devices.

Plastic plates with 384 individual wells, with samples in each well, were individually placed into a thermal cycle machine for a series of heating and cooling cycles. Each plastic plate fit into a matching metal plate and the two were pushed together with a locking lid. The warping of the plastic as a result of the varying temperatures made it very difficult to remove the plastic plate. Technicians rocked the plates back and forth using high force and awkward hand postures one hand at a time (Figure 18). This led to hand injuries and wasted time. A suction cup tool was designed to attach onto the top of the plate allowing the technician to lift the plate straight up and out of the thermocycler with minimal resistance (Figure 19).

Early reporting of symptoms and rapid response

An ergonomics specialist and nurse were added to the onsite staff so employees with concerns could ask questions, receive advice, and review their work tasks and postures. They were available to visit workstations and discuss specific concerns of the employee about the work task or area. The on-site nurse provided consultation and first aid as indicated. These on-site resources helped promote early reporting of symptoms or problems, allowed for a rapid response to emerging issues, and sent a message that safety and wellness were important elements of the organization’s culture.

Prior research demonstrates that employees should be encouraged to report early symptoms of pain, discomfort and fatigue to their supervisors. Early reporting of symptoms coupled with rapid responses with administrative changes or ergonomic work modification can prevent minor symptoms from escalating to reportable injuries, lost time, and disability (Loisel, 1997). For many workers, for personal and organizational reasons, a more typical response to discomfort is to ignore or downplay the symptoms.

At the JGI, efforts to promote early reporting were integrated into regular one-on-one conversations between employees and supervisors. Supervisors thanked employees for openly communicating with them about their discomfort and efforts were made to include employees in helping to identify inefficiencies in work and changes that could help reduce discomfort. Prompt actions to provide health and ergonomic support, when indicated, provided employees with the message that their comfort and safety was valued by the organization. This is consistent with the recommendations of the American College of Occupational and Environmental Medicine

(ACOEM, 2006), which cites the successful experience of North American (primarily Canadian) employers who have “demedicalized” the stay-at-work process, assisting employees in learning to cope with low-level discomfort from musculoskeletal problems with self-treatment (e.g., ice packs; medications not requiring prescription) and adjustment of work tasks while ergonomic changes are being put into place.

For several months after work restarted in January, 2008, technicians were asked to complete a daily comfort survey to establish the acceptability of reporting symptoms and to aid in the early and rapid response process. All survey forms were reviewed by the on-site ergonomist. If increases in discomfort were reported via the comfort survey, the ergonomist met one-on-one with employees at their work locations and discussed aspects of the equipment or work methods that may be contributing to the change in comfort level.

Case management

Proactive case management is a tool to facilitate effective communication and information regarding employees who are experiencing discomfort and/or have work-related injuries, and their supervisors. On a bi-weekly (and later, monthly) basis representatives from Human Resources, Safety, Ergonomics, and Health Services met together to discuss challenges, progress and plans for all employees who had work-related injuries or who reported increasing discomfort. The supervisors of the respective employees attended the meetings to provide their input. The proactive case management meetings provided a forum for everyone to work together to ensure that the needs of the employees were being met to facilitate recovery, injury prevention, and/or help return injured employees to work. The meetings also improved communication among staff and helped eliminate mixed messages to employees.

Communications

A quote attributed to various writers, “The single biggest problem in communication is the illusion that it has taken place", is relevant to the situation at JGI (Whyte, 1950). For several years prior to the “Production Stand Down”, a prominent method of communication by management to employees was to display productivity statistics, failure rates, and information about injuries on large monitors throughout the production areas. During the Stand Down, technicians provided feedback that this constant reminder of production quotas problems was adversely affecting their morale and was not helping to improve either productivity or safety. After the Stand Down, management changed the monitor messages and instead projected employee-organized wellness activities and technician accomplishments, such as winning an Ergo Cup® award.

Management implemented several formal and informal communication strategies, both two-way and multi-channel. During the beginning of the Stand Down senior management clearly demonstrated their support for employee involvement and engagement in identifying and solving the organizational issues. Small group meetings were held to allow employees to speak openly with facilitators to express their frustrations, ideas and suggestions. A key issue raised was the role of management in taking responsibility for the organizational factors that were contributing to the injuries, rather than blaming employees for production problems. In addition, quarterly “All Hands Meetings” were held in a setting where all members of the production staff were in the same room together so that messages could be communicated to all parties in a consistent manner.

Additional communications channels were established with the goal of reaching staff in a variety of ways. A Safety Blog was created to serve as a 'suggestion box' for any safety concern or suggestion, and placed on the home page of the JGI internal website to serve as a vehicle for sharing and disseminating two-way safety communications. Employees could submit an anonymous safety suggestion or observation as well as post safety-related updates and information. When indicated, actions were taken on recommendations and those actions were posted on the blog. The Safety Blog posts were also reviewed on a monthly basis by the Safety Culture Working Group to ensure dissemination of the safety information throughout the organization. During the All-Hands meetings, employees who submitted safety suggestions were recognized in a positive manner.

The multi-pronged approach to reach employees also included emails, mandatory trainings, and even in the bathrooms. The Safety Culture Working Group developed light-hearted “Potty Trainings” - internal communications in bathroom stalls. Potty Training communications were updated on a monthly basis, applying safety and ergonomics not only to jobs at JGI but also to other aspects of life, including traffic safety. Online ergonomics training was also required for all employees and supervisors and applied to computer use at work and home. Individual ergonomics workstation and work process evaluations were available to all employees. A practice laboratory workstation with functioning tools was built for the training of all current and new employees on laboratory protocols and techniques, using a design developed with input from JGI staff (Figure 20).

2008-2015: The Organization Post-Disruption

From 2008 - 2015, the productivity gains at JGI were substantial (Figure 21). For example, between 2011 and 2012 production increased threefold as a result of new technology. The efficiency of these new technologies allowed the JGI to operate on day shifts only and no longer required 24/7 operations. The process for adopting and deploying new technology integrated ergonomic design and considered human-systems issues before implementation in production. Technicians worked with engineers to integrate the new technologies efficiently and effectively.

During 2008 – 2015, JGI integrated two state-of-the-art liquid handling robots that fully automated certain manual processes and improved sample management and handling. Lean and six-sigma training provided technicians with additional tools to identify areas for optimization and improve workflow. Quality control steps were incorporated into the “islands of automation” design that not only improved the safety and ergonomics of the work centers, but created more available capacity to support the increasing throughput of the organization.

Currently, the majority of the production line processes at JGI are fully automated with minimal human interaction, performing world-class genomics with production steadily increasing year-to-year (JGI, “About Us”). Supporting information systems provide reports to identify trends in processing fluctuations to minimize re-work.

Discussion

This is a case study of an organization that had outgrown its capability to respond to the rapid integration of new technologies, customer needs and employees’ ability to keep up with demands. The intermediate strategy to meet increasing production demands was to adopt semi-automated equipment as “islands of automation” with inadequate consideration of how the technology integrated with the existing production process and the additional physical demands that it placed on the technicians. When the physical demands exceeded worker physical capabilities, an unsustainable production system emerged. The human injuries and inefficiencies introduced by this approach to technology adoption led to significant disruptions of production. The solution was an organizational-wide, participatory examination of the sustainability of its approach, and the development of an interdisciplinary path forward.

Organizations spend significant resources on the human costs associated with selection, training, retention and, notably, worker injuries. Injuries, and the long periods of discomfort, pain and decreased performance that often precede the onset of an injury, are significant detractors from organizational effectiveness. The preferred strategy for dealing with new technology and increased production demands is to prevent the inefficiencies and injuries from happening through the careful consideration of ergonomics and safety issues prior to the introduction of the new technology. A second line of defense is the use of administrative controls, such as job enlargement and job rotation, to safeguard people from excessive exposure to risk factors for fatigue and injury. As seen in this case study, the use of administrative controls can be useful as supplements to a proactive approach, but their effectiveness without Macroergonomics is much less.

Occupational health and safety control measures generally yield favorable returns on investment. For example, the International Social Security Association, in a study spanning 19 nations, found a mean benefit-to-cost ratio (which they called a “Return on Prevention”) for occupational health and safety interventions of 2.2 (ISSA, 2013). Similar results were found in a review of ergonomics interventions in a wide variety of industries in the U.S. State of Washington (Goggins, 2008). The authors summarized their findings as follows: “Commonly reported benefits [of ergonomic interventions] included reductions in the number of work-related musculoskeletal disorders or their incidence rate, as well as related lost workdays, restricted workdays, and workers' compensation costs. Additional benefits reported were related to productivity, quality, turnover and absenteeism…Benefits reported were largely positive, and payback periods for ergonomics interventions were typically less than one year” (Goggins, 2008). An additional benefit of improved employee morale have been cited in several literature reviews of successful occupational health and safety programs (EU- OSHA, 2009; Behm, 2009).

Rempel, et al (2006) tracked the effects of the installation of a simple forearm support designed for computer work, and considered the cost of the intervention plus installation as compared with the savings associated with preventing neck/shoulder disorder cases. They calculated a payback period of 10.6 months. These calculations do not consider additional cost savings, such as those associated with temporary replacement employees, and the benefits of symptom improvement for those employees who had not yet filed insurance claims. Inclusion of indirect costs such as these would yield an even greater return-on-investment. Similar arm support strategies were included, with good results, in some of the job improvements in the JGI case study discussed in this paper.

Organizations operating in environments with rapidly changing technologies face another challenge. These technologies demand continuous change and modulated responsiveness to fluctuations in the environment. “Requisite variety”, originally conceived of in cybernetics, and later referenced by Weick (1987), suggests that organizations must develop a variety of responses proportional to their increasingly complex environment in order to survive.

Organizations in stable and less technology-dependent environments require a variety of responses, but those in complex and rapidly changing environments face changes with greater frequency and amplitude, and need to be able to respond in a greater variety of ways to remain effective. This poses a unique challenge for an organization as it seeks to reduce its uncertainty through effective design, processes and worker protections in an environment that is continually changing (Thompson, 1967).

Finally, a macroeconomics or systems view engages the key players in the change process; the technology experts, management, and those whose work will be directly affected. This participatory approach was originally introduced in Japan by Kogi and Noro and later expanded upon by Noro and Imada (1984), and in Northern Europe (Elden, 1986) and North America (Liker, 1995) during the 1980s. It has been applied in a wide variety of industries ranging from agriculture to the maintenance of public utilities (Janowitz, 2000). Using a participatory ergonomics approach, for example, Imada (2002) demonstrated the ability to reduce motor vehicle accidents, industrial injuries and lost workdays using worker involvement and system-wide changes in a large petroleum transport organization.

Conclusions

This organizational case study demonstrates how technological changes can drive organizational change. The complexity surrounding this particular industry highlights this demand, its effects and the results of highly adaptive and successful intervention. The experiences in this case highlight the importance of a broad systems approach to solving multifaceted organizational issues. Keys to this organization's success include: A courageous management willing to rethink an entire production system, a multidisciplinary team coordinating their efforts to a common goal, engagement at all levels of the organization, a participatory and open approach for everyone to be involved, and the use of employee feedback and honest listening to help guide actions.

The human factors and ergonomics professionals were embedded as part of the management and technical team to guide the change process. While on the surface, the production disruption appeared to be due to the employee injuries, the causes were more than physical. Underlying problems with the tools, equipment, work process and productivity metrics had to be identified and addressed in order to bring production process to sustainability and to improve safety and morale. The solution required more complex and multidisciplinary strategies that involved management, supervision, technologists, safety professionals, medical staff, human resources, and the people performing the work. This experience demonstrates the importance of an approach that integrates humans and systems to address technology-driven change.

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FIGURES

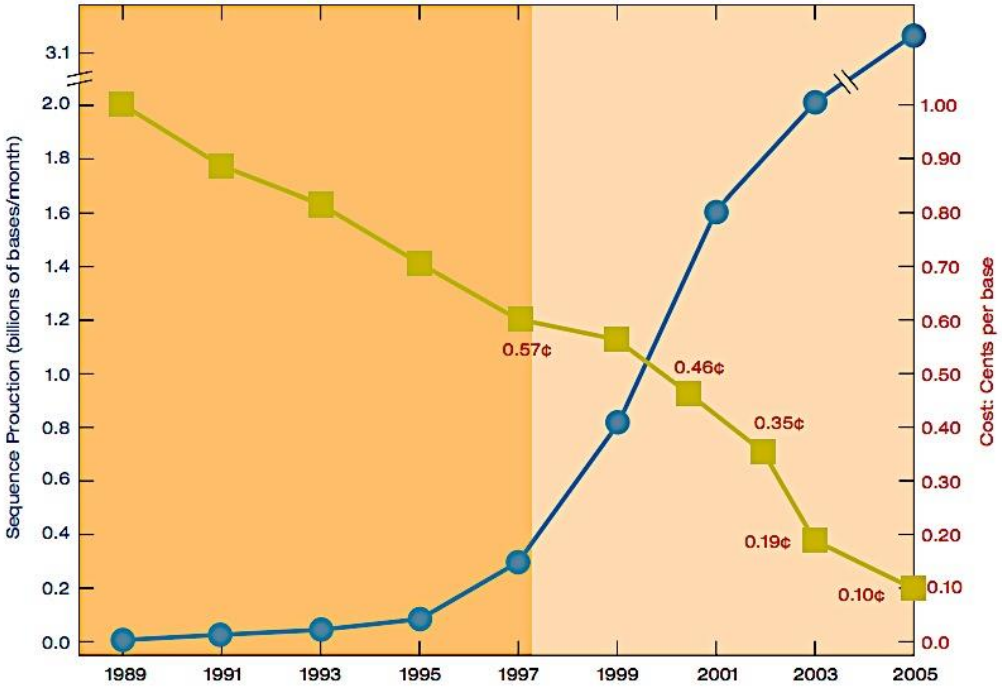


Figure 1. Production Output. Change in production output (left vertical axis, blue line), and decrease in cost per base (right vertical axis, green line) at JGI between 1989 and 2005 (JGI was formally established in 1997). Note scale change for production output from 2003 to 2005.

Figure 2: Hand Intensive Work. Repeated manual pipetting used for sample preparation.

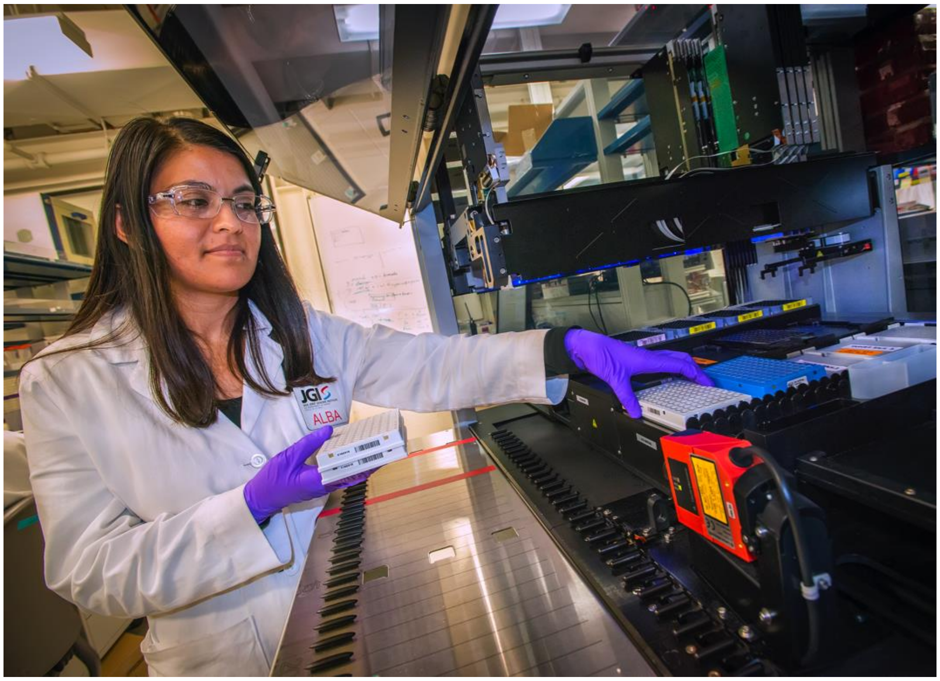


Figure 3: Hand Intensive Work. Manual feeding plates into a semi-automated machine.

Figures 4 to 6. Awkward Postures. Repeated forceful pinch tasks and awkward wrist and shoulder postures.

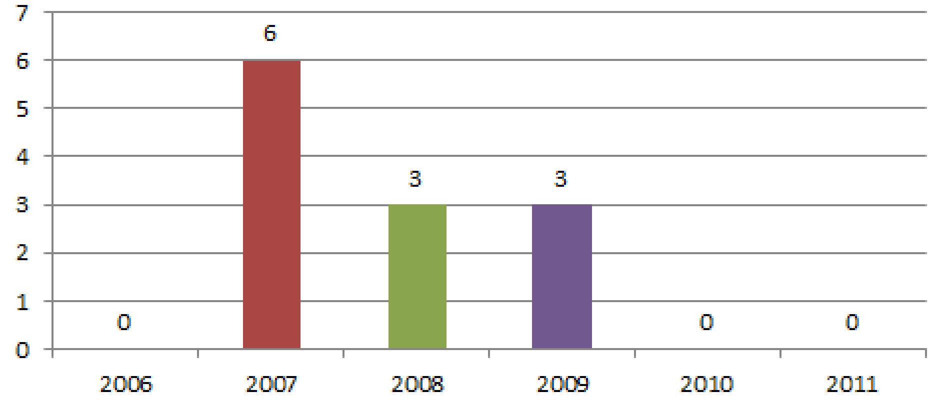


Figure 7. Injuries. New upper extremity injuries related to hand intensive work.

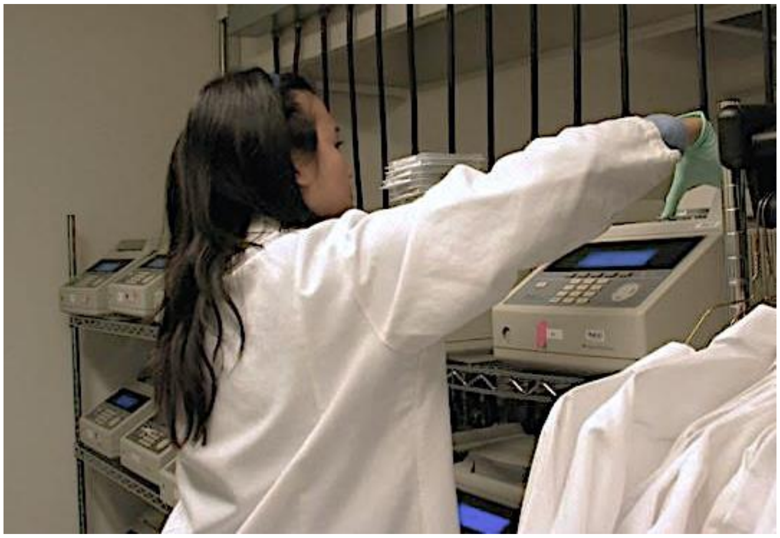


Figure 8. Awkward Postures. Shoulder elevation and inefficient reach due to poor placement of frequently used equipment in production facility.

Figure 9 (left). Improper working height. Workstation height too low for task.

Figure 10 (right). Proper working height. Electrically height-adjustable workstations added to eliminate bending and wasted motions.

Figure 11. Participatory Design Process. Group evaluation of prototype biosafety cabinet design with supervisor (center), ergonomist (left), and technicians.

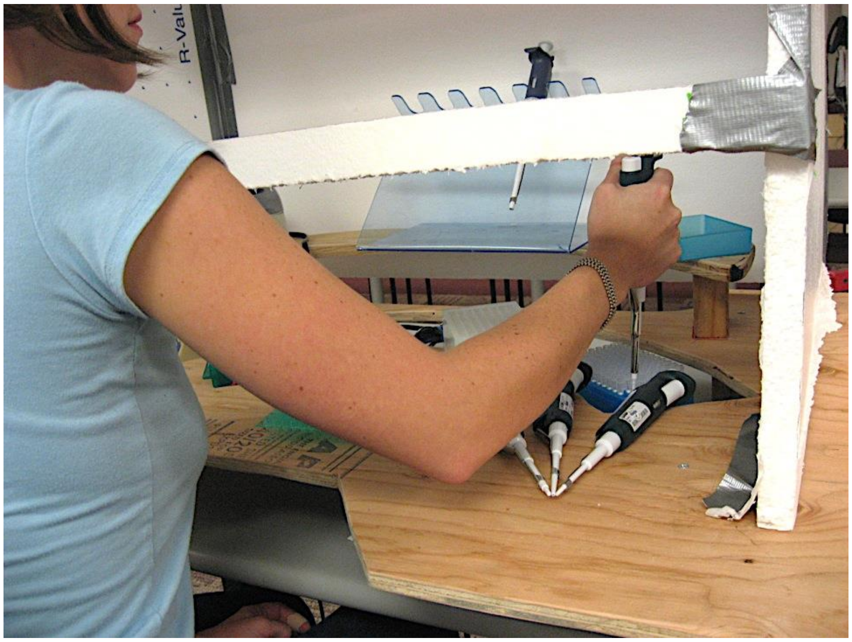
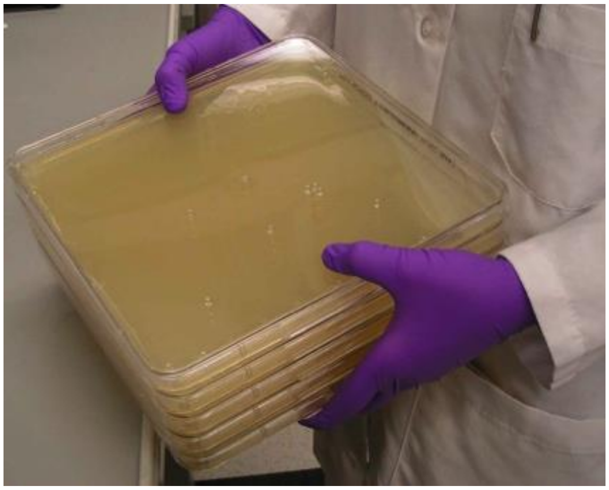


Figure 12. Participatory Design Process. Usability testing of a prototype biosafety cabinet.

Figure 13. Final Design of Biosafety Cabinet Design. Design includes sunken area for commonly used equipment to reduced shoulder postures and improved work efficiency.



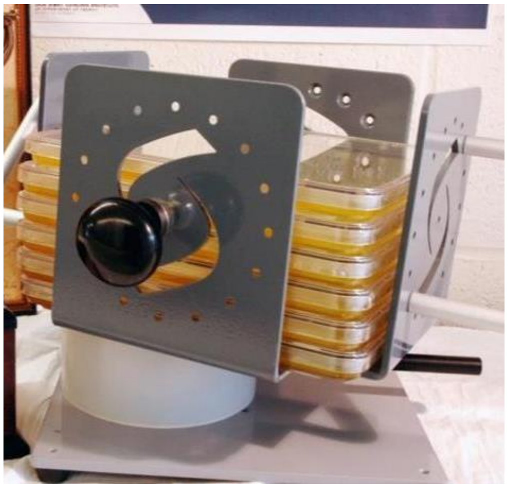
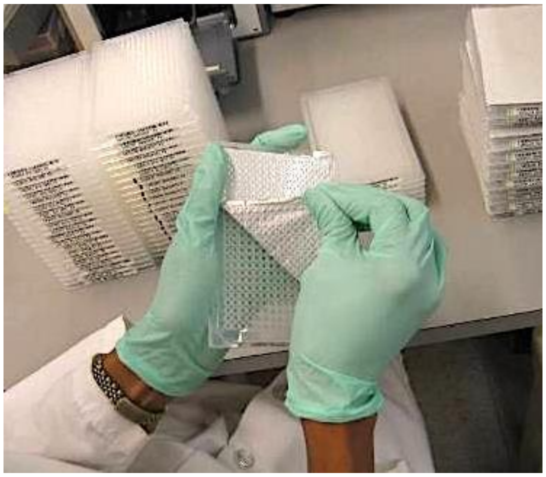


Figure 14 (left). Before. Heavy plates were awkwardly gripped with 2 hands and shaken (left). Figure 15 (right). After. The modification, “Shake ’N Plate”, an easy-to-hold fixture that held the plates and could be easily moved by hand or by a computer-controlled motorized base. The concept was originated by a JGI technician and refined with participation from other technicians and engineering staff.



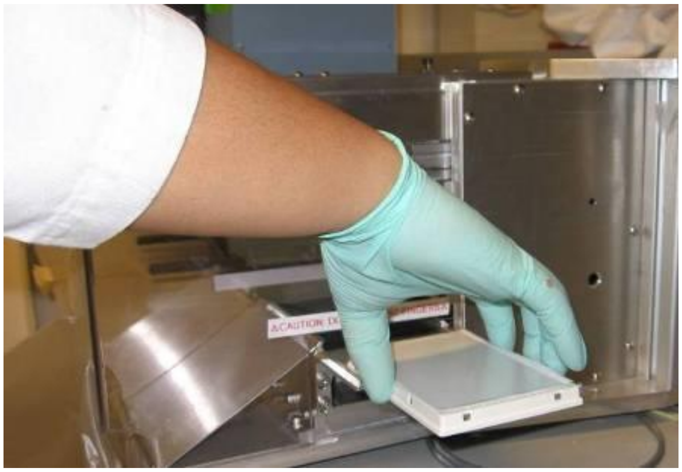


Figure 16 (left). Before. Pulling the aluminum seal off a 96-well plate requires near maximum hand strength and was identified by employees as one of the most physically demanding tasks.

Figure 17 (right). After. A custom machine was designed and built to mechanically remove the seal. Loading the plates is quick and easy.

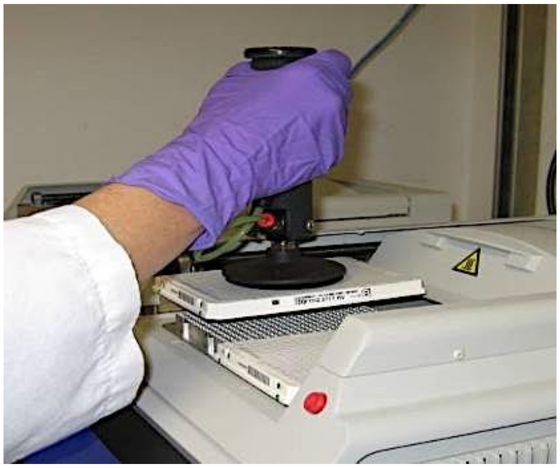


Figure 18 (left). Before. Plastic sample plates were difficult to insert and remove from a thermal cycler because they had been frozen at -80^{o} C and then heated on the machines. Plates often expanded and warped, requiring high force in an awkward grip to remove.

Figure 19 (right). After. A suction cup with a handle was developed to make this task quicker and easier, reducing the risk of hand injury.

Figure 20. New Training Workstation. Workstations were set up for practicing new procedures, cross-training in different tasks, and learning to use new equipment or workstation layouts.

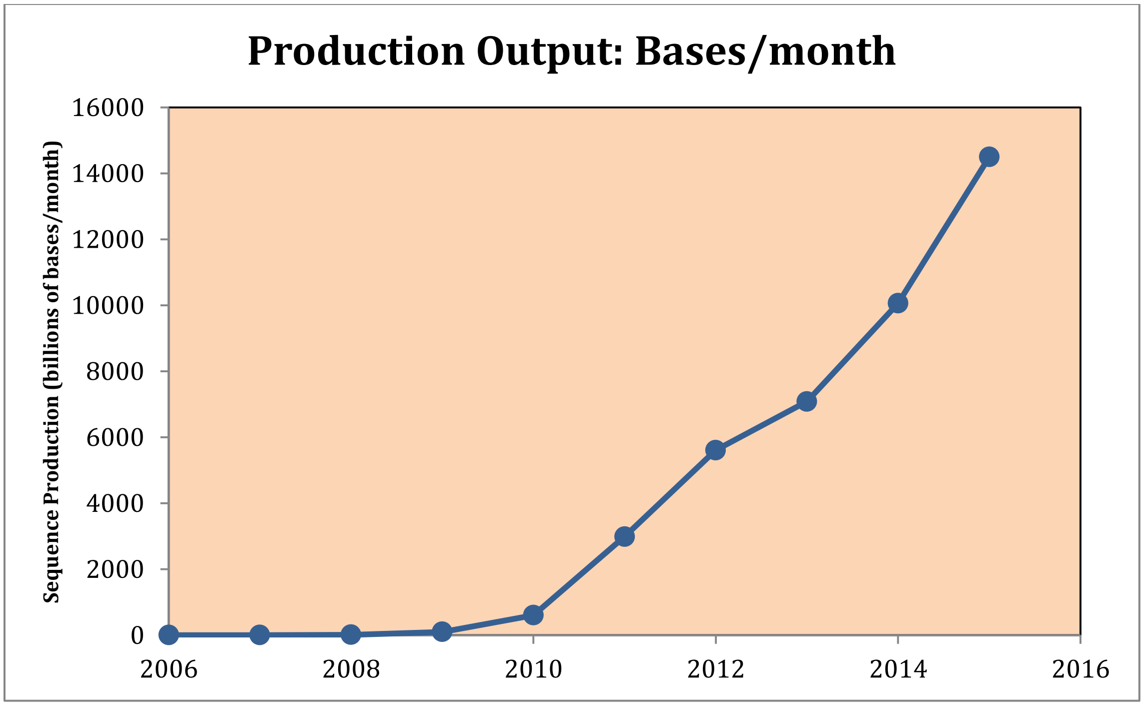


Figure 21. Production output from 2006 and 2015 at JGI after the intervention.

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