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Application of Cognitive Task Analysis in mining operations

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ABSTRACT

Through the advancement of human-machine interactions in various fields, understanding beyond the technical components has become prominent. Traditional methods for analyzing human behavior in a work setting, which mostly centralize in identifying material and observable traits, don't seem to fit modern technology and systems used in various industries today. The concept of Cognitive Work Analysis (CWA), in this regard, has gained interest in academic and business settings in the last few decades. A cognitive analysis expands the observation of worker's interactions to a more cognitive and behavioural level and sets a safety standard for a well-designed project. This research essentially aims to fully comprehend the five steps of CWA through the examination of cases and finally, seeks possible applications in the mining industry, where accidents due to human error are impactful. In this paper, an initial proposal of a CWA model for the mining industry is developed based on an existing model of quantifying human error in maintenance in various industries.

KEYWORDS: cognitive work analysis, work domain, human behavior, safety.

1. INTRODUCTION

Many industries operate in hazardous fields, including but not limited to nuclear power, manufacturing, aircraft operation, and mining. While the successful human-computer interaction is generally ensured, there are still a number of concerns and room for improvement when uncertainties are taken into consideration. While there are many possible reasons for industry accidents, human error is considered to be one of the main causes. Furthermore, the mining industry, being acknowledged as a particularly hazardous industry, experiences numerous accidents caused by neglect, lack of knowledge, or simply by a combination of human error factors. In order to better comprehend the design process of such hazardous and complex systems, a number of cognitive analysis tools have been introduced, such as Cognitive Work Analysis (CWA).

This analysis is defined as a "conceptual framework that makes it possible to analyze the forces that shape human-information interaction" by Fidel and Pejtersen (2004). Therefore, the psychological and cognitive thought of a worker are important factors. Interview processes and analysis tools are used to uncover the operator's approach to a human-machine system, beyond the formal training. Qualified workers can sometimes be unaware of their actions, despite their motivation to fully complete the tasks. This might occur due to a number of conditions such as mental and physical state, work environment, and the equipment's design. Later on, the steps of the analysis will reveal that through document analysis, interviews, and observations, besides cognitive processes, the cognitive work system includes five different aspects. The focus of the present study is to discuss the application of an improved cognitive work analysis to a mine environment. The paper firstly elaborates on the background of the research and its reflections in the related literature; this is followed by the steps for cognitive analysis data collection; and finally based on those data, an initial cognitive analysis model is formed in order to quantify the cognitive work quality of a mine.

2. RELATED WORK

Behavioral researchers in different fields address issues such as analyzing the process of decision-making under uncertainty (Kahneman & Tversky, 1979) and the effect of cognitive and motivational biases on the output of risk analysis (Montibeller & Winterfeldt, 2015). More specifically, engineering systems have also tried to comprehend the factors affecting human performance and potential ways to improve it (DoE, 2009). Among many others, some of the techniques and concepts mentioned in these papers, such as Skills-Rules-Knowledge Taxonomy and Strategic Analysis, are related to the specific concept of Cognitive Work Analysis, which is the basis of this paper.

The domain of human factors engineering started in the 19th century during the industrial revolution, where physical tasks were repetitive and required none of the cognitive ability necessary in today's

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work domains. As such, the first forms of task analysis simply question the best possible and only way to perform a task (Vicente, 1995). However, in the case of unanticipated events taking place, this type of analysis would not be prepared since it only involves the completion of a specific task.

Through the late 20th century, when the need for a more adaptive tool arose in order to meet the demands of a more complex system, the concept of cognitive task analysis was introduced. CWA was then developed by Rasmussen in 1986, in order to provide a more general approach that examines the task, the work domain, the strategies, and the cognitive processes all at the same time. Also, it was identified that nuclear power plants are extremely vulnerable domains in the sense that they are fairly complex systems, and accidents mostly occur when the incident is unfamiliar to operators (Vicente, 1995).

Starting from 1989, the cognitive work analysis (CWA) changed its scope towards a different framework called Ecological Interface Design, whose focus is to design the interfaces in complex socio-technical systems (Naikar, 2011). The concept found applications in process control systems of various domains, such as petrochemical and nuclear power, addressing both small and medium-scale problems. In the following decade, this concept was applied to questions regarding training needs of systems in many different domains (Pawlak & Vicente, 1996; Jamieson, 2007; Lau et al., 2008).

Therefore, the development of CWA started with the consideration of nuclear power plants but can surely be adapted to many other hazardous industries where conditions are similar. Hazardous industries with high levels of human-machine interaction and uncertainty, such as mining, would surely benefit from further applications of Cognitive Work Analysis.

3. COGNITIVE ANALYSIS DATA

This section aims to elaborate the five steps of the Cognitive Work Analysis (CWA) to be used in the mining industry, and also, introduce general data structure for the model in the next section. Each step of this analysis serves a different purpose of elaborating on more detailed aspects of data collection.

3.1. Work Domain Analysis

Having defined the scope and purpose of the CWA, the first step is to apply Work Domain Analysis, which illustrates the domain where the task is performed. All, the purposes are determined and the functional units are illustrated. The mining domain can be described as complex, combining together different operations such as drilling and blasting, materials handling, loading-hauling or concentration, mineral processing, equipment reliability, and so on.

It is essential to fully comprehend the aspects of the work domain and define the external constraints to be faced. The Work Domain Analysis helps to realize what the system is supposed to do rather than what it is actually doing. In this step, the recommended tool is Abstraction Hierarchy, along with Abstraction Decomposition Space (Jenkins et al., 2008). Through the examination of documents, operation manuals, and interviews with subject matter, the functional purpose, the elements and the constraints in the system are revealed.

3.2. Control Task Analysis

This second phase takes the analysis a step further and evaluates the required task in the working system. The necessary task/operation to be performed to meet the functional purposes are examined in detail. For example in drilling-blasting operations cognitive experts should understand, from a human interaction perspective, the following information: drilling geometry, drilling equipment maintenance, drill bit replacement, bit-rock interaction, explosive storage, type and placement, operator performance, and inventory management.

The acquisition methods are Cognitive Walk-Through and study of work practices (Lintern et al., 2004), and the tools recommended for this step by Vicente (1999) are either Decision Ladder or Contextual Activity Template. These steps reveal the relevant detailed information regarding the comprehension of the task, the steps to make a decision, and which levels of knowledge the operator uses.

3.3. Strategies Analysis

Strategies Analysis constructs the third phase of the CWA. After outlining the work domain and the required task in previous stages, the strategies analysis moves towards the specific factors that may prevent the task from completion and what are the most efficient ways to complete it. All human factors affecting a mining operation are documented.

The acquisition methods are Critical Decision Methods, Interaction Analysis and Verbal Protocol Analysis (Lintern et.al, 2004). After gathering the necessary information, the recommended tool for demonstration is Information Flow Map (Vicente, 1999).

3.4. Social Organization and Cooperation Analysis

The fourth step of the CWA is Social Organization and Cooperation Analysis. As the name suggests, this step investigates how the team members interact with each other within the constraints that are posed on the team as a whole. This stage moves from individual to team, with the analysis being conducted in terms of team performance.

The acquisition method is Communication and Interaction Analyses (Lintern et al., 2004), which mainly discovers the relationship of actors through verbal processes.

3.5. Worker Competencies Analysis

The final phase of the analysis is Worker Competencies Analysis. It aims to discover the factors affecting the behaviors of actors within a specific workplace, when different situations are in question. Through the review of previous steps such as the Decision Ladder and Repertory Grid Analysis (Lintern et al., 2004), a specific tool called Skills Rules Knowledge Taxonomy is formed (Vicente, 1999).

When a specific strategy for a specific task is considered, The Skills, Rules, Knowledge (SRK) Taxonomy demonstrates both the SRK information and the information about the activity and how different they are in each knowledge state (Jenkins et al., 2008). The SRK Taxonomy classifies human behavior in relation to various restrictions in a workplace. As a result of this analysis, Vicente (1999) suggests that the most important parts of cognitive processes can be awakened and used for the betterment of the design. Furthermore, according to Kilgore and Cyr (2008), the SKR inventory can also refer to the worker competencies that are essential for task completion.

It is important to mention that this paper attempts to provide a different approach by including the analysis of physical and mental fitness of the workers as well. These elements are specifically found important in the sense that the cognitive factors for the workers strictly depend on these conditions. This will be introduced in the following sections where the model is presented.

4. COGNITIVE ANALYSIS MODELLING

4.1. Cognitive Work Quality Factors

In an attempt to form an applicable and similar tool in mining to quantify the CWA explained in the previous section, some related research is summarized here. One of the most significant papers develops a method to quantify human error using graph theory and matrix approach (Kumar and Ghandi, 2011). The current study adopted this method and combined it with the extensive framework of CWA as an effective tool in assessing mining reliability.

In an attempt to understand the complex structure of the mining domain, Cognitive Work Quality (CWQ) is computed as a percentage describing the qualities of the mine domain, such as its management, safety, and feasibility. The information derived from the cognitive analysis data in Section 3 forms the CWQ factors. Each factor has different characteristics, each of which was assigned a quality rating ranging from “Excellent” to “Poor”.

4.2. Quantifying the Cognitive Work Quality Index

In order to calculate the cognitive work quality index for a task, it is crucial to determine the severity value of each factor, as well as the influence between these factors. First of all, each of the eleven CWQ factors mentioned in Table 1 (See Appendix 1) has a weight (ranging from 0 to 1) attributed to it, which represents the role and importance of a factor for the studied task. The total sum of the weight should be equal to one, such as:

$$W_{CWD}+ W_{MD\&E}+ W_{TD}+ W_{TI}+ W_{SA}+ W_{S}+ W_{MC}+ W_{T\&C}+ W_{PR}+ W_{P\&MF}+ W_{CDT} = 1$$

The higher the weightage of a factor, the more significant it is in the assessment of cognitive work quality.

Secondly, as seen in the table in the appendix, each factor has different attributes, “Cognitive work characteristic”, associated with it. Each of those characteristics is rated from a scale from 5-excellent to 0-poor. For each factor, the sum of its characteristics ratings corresponds to the level value, L_i. As an example, to know the level value of the “Tools Design” factor, we would need to sum the rating assessed for its characteristics such as: “Design Compatibility”, “Efficiency for Task Completion” and “Availability of Equipment”.

Based on the weightage (W_i) and the level value (L_i) of each factor, Quality value, Q_i is formed as following:

$$\text{Quality value, } Q_i = W_i \cdot L_i$$

Finally, the influence between two factors, F_{ij}, with a scale from 5 to 0 such as 5- Strong Influence, 3- Medium Influence, 1- Weak Influence, and 0- No Influence, are assessed. These weightages and influences between factors are assessed by experts using human reliability analysis techniques. These techniques, such as THERP, CREAM and NARA set an error probability to the execution of necessary actions taken by the workers at every cognitive work quality factor. Many aerospace industries, such as

NASA, use these techniques to considerably reduce operational and procedural errors (NASA, 2010).

The quality values Q_i and the influence values F_{ij} are placed in a matrix as followed, with the permanent of this matrix being the cognitive work domain quality index.

$$CWQ_{index} = \text{Permanent of} \begin{bmatrix} Q1 & F12 & F1M \\ F21 & Q2 & F2M \\ FM1 & FM2 & QM \end{bmatrix}$$

With *M* being the number of factors involved for the work domain of the mine.

4.3. Cognitive Work Quality Results

The cognitive work domain quality index is turned into a percentage by computing the index for the ideal case work quality and for the worst work quality, such as:

$$CWQ\ (\%) = CWQ_{Index}\text{-}CWQ_{Ideal} \ / \ CWQ_{Ideal}\text{-}CWQ_{worst}$$

Table 1 shows the range and signification of the Cognitive Work Quality percentage obtained.

Table 1: Cognitive Work Quality Ratings and Recommendations.

Rating range	**Cognitive Work Quality**	**Recommendations**
85-100	Excellent	Mine domain does not require any major adjustment.
70-85	Good	Minor adjustments are needed to attain excellency in the mine domain.
60-70	Average	The mine domain is efficient but major changes are needed to improve its quality.
45-50	Poor	Enhance the management system by seeking advice from suitable experts.
0-45	Insufficient	The mine requires major update in its system. Should close until a safe and feasible environment is attained.

As can be observed, this tool can be used to evaluate the standing point of a mine site through a thorough examination of all its subsystems and finally, forming a set of recommendations in which the weakest parts would be improved. Furthermore, this tool can also be used to determine which of the factors contribute to the final rating more, with a simple regression type analysis.

While there are a number of other design solutions that can be provided within this framework, specific recommendations to improve working performance may need further attention. According to the rating range in which the mining system is in, some adjustment can be made to the work quality of operators regarding the task performance. Therefore, today, many mining companies track the workers' general performance such as the production targets achievements, computer tracking, safety performance, reported injuries, safety procedure flaws, daily physical/mental state observation by the supervisors, meeting the task deadlines, and drug testing when required, all with the purpose of reducing human error.

Finally, the prospect theory by Daniel Kahneman explains that decision-making appears subjective for every human worker, and so, assessing probabilities to errors (weightage and influences) could lead to biases in the cognitive work quality results (Kahneman & Tversky, 1979). Also, the experts' judgments may lead to biases on choosing the characteristics rating. The field of neurotechnology could be used in the future to directly connect the consciousness of an individual with equipment and improve human-machine interaction in the mine site.

5. CONCLUSION

The Cognitive Work Analysis (CWA) is a relatively new and powerful tool in assessing the workplace in every aspect. Taking its roots from 19th century ergonomics research, this type of analysis evolved from traditional terms and finally, has room for cognitive research as well. The method allows the design to be prepared for unanticipated events by detecting the constraints on task completion. As it analyzes aspects independent from the task and the actor, CWA provides a more flexible and comprehensive point of view. Furthermore, analyzing all the different aspects simultaneously leads to understanding and forming strong interactions between these aspects, which is beneficial for the design.

As a highly risky industry with constant human-machine interaction, the mining industry is a good candidate for the application of the CWA in order to improve its system. After data gathering and modeling, the Cognitive Work Quality was assessed using probability factors. The quantified quality found is associated the mining system state and possibly, can present some specific recommendations. Furthermore, factors affecting the workers are better addressed than in Cognitive Work Analysis, simply because mining is found to be difficult to manage in terms of human factors and reliability, moreso than any other industry. Mining systems and many other hazardous industry domains can benefit from the introduction of this framework in quantifying and improving the quality of design in the work environment. Since this is only the initial stage of this research, a case study should be conducted on an actual North American mine to test its efficacy.

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Appendix 1: Cognitive analysis modeling table for the quantification of the Cognitive Work Domain Quality (CWQ).

Cognitive Work Quality Factors (CWQ_i)	Cognitive Work Characteristics	Characteristic Rating 5-Excellent; 3-Good; 1-Average ;0-Poor
MINING DOMAIN		
Characteristics Of Mine Domain (CWD)	System Functionality	Defining the function and the purpose of the system and creating a work environment accordingly.
	Constraint Management	Effectively managing the environmental, legal and technical constraints posed on the working domain.
	Target Attainability.	Achieving the defined common goals and targets of the domain.
Mine Design And Environment (MD&E)	Mine Planning And Scheduling	Meeting long range planning goals by creating an efficient mining production plan.
	Safety Precautions (Mine And Assets)	Ensuring a safe environment for employees and equipment (i.e. Ground support, geotechnical design).
	Operation System	Attaining optimal operation system. Creating the most time-efficient schedule to meet production deadlines and targets.
CONTROL TASK ANALYSIS		
Tools Design (TD)	Design Compatibility	The equipment suitability for the required task.
	Efficiency for Task Completion	How efficient is the current set of tools for the task completion (quality, safety, productivity and so on).
	Availability of Equipment	Having an easily accessible and available equipment for the task completion.
Task Implementation (TI)	Guidelines and Procedures of Task	Ensuring the accessibility of information sources and data.
	Performance Criteria Well-Defined	How well-defined is the criteria for assuring outstanding performance.
STRATEGIES ANALYSIS		
Strategy Analysis (SA)	Management of Uncalculated Event	Handling unanticipated events and being prepared for novel situations.
	Availability of Methods of Task Completion	Ensuring the accessibility of available methods and different strategies pathways.
SOCIAL ORGANIZATION AND COOPERATION ANALYSIS		
Supervision (S)	Clarity of Instructions and Procedures	Excellent communication is necessary between the employees and supervisor in order to assure optimal and safe performance.
	Mine and Asset Sustainability	Maintain mine and assets quality to be fit for continuous activity.
	Time Management	Activities must maintain their time deadlines and ensure that tasks are completed on time.
Mining Culture (MC)	Incentives	Encourage good working habits by evaluation financial business and safety performance and rewarding with salary and bonus.
	Mining Community Involvement	Workers participate in volunteering and community activities in the mine domain
	Safety and Emergency Plan	The mine site is well-structured for any possible emergency situation, with specific plans and guidelines.
Teamwork and communication (T&C)	Roles and Responsibilities	Roles and responsibilities for each actor is different and should be well-defined to comprehend abilities and specializations.
	Communication	Information flows freely according to the organizational structure of the mine domain, and the different workers have access to that information by efficient communication system.
	Involvement and Coordination	The activities of the workers require a certain level of coordination and feedback mechanism.
WORKER COMPETENCIES ANALYSIS		
Performance Requirements (PR)	Formal/Continuous Training	Level of formal and professional training completed by the workers.
	Skill-Based Behavior	Automated responses to alerting events. Does not require much cognitive process. Mostly used in physical processes, i.e, operating a machine.
	Rule-Based Behavior	The workers are able to verbalize their thoughts and generate behaviors through their experiences, i.e, following safety instruction for truck haulage.
	Knowledge-Based Behavior	More complex and demanding process where the workers take the individual and system goals into consideration with analytical reasoning and problem solving skills
Physical And Mental Fitness (P&MF)	Arm, Leg, Back Strength And Endurance Level.	Physical condition to conduct any required task using mining equipment.
	Emotional Stability	Stress management and handling unexpected situations. Mental health issues.
	Concentration Alertness And Memory	The workers are able to stay focused during task completion and memories important details and facts.
	Self-Satisfaction	The workers are confident in the abilities and satisfied with the way of task completion.
	Acute Sight	The workers have a great vision and a rapid reflex to any situation.
Cognitive Demand Of Task (CDT)	Logical Reasoning	Dealing with novel situation by improving knowledge-based behavior and high level of logical reasoning.
	Perception Skills And Knowledge	Perceiving a thorough outline of the task and applying knowledge to a problem with an extensive perspective
	Stress Handling Capacity	Managing the stress facing a situation or a problem.
	Learning Skills and Experience.	The ability to learn and adapt new and professional knowledge; level of experience of workers.