Operational Decision Making in Aluminium Smelters

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Abstract. Many computer systems incorporating artificial intelligence have been introduced for use in industry to assist in making decisions and controlling processes. However, decision making in a complex industrial plant, such as an aluminium smelter, involves psychologically related factors such as intuitive reasonings, operator response characteristics, perception of risk, and implication of rewards. While a significant body of work does exist on decision science, research concerning human interaction with process control systems is still at the development stage. The work reported here aims to meet the needs of the process industry by incorporating human factors and decision making strategies into computer programs such as a supervisory control system for aluminium smelters. A case study on the control of the level of the liquid electrolyte was carried out to firstly facilitate an understanding of the variables, including human factors, on process control. It was found that the availability of crushed solidified electrolyte material had a significant impact on the level of the liquid electrolyte, while the implementation of a supervisory control system had a certain impact, management and leadership styles also had a significant influence.

Keywords: Supervisory control system, decision making, human and system interaction, process control.

1 Introduction

1.1 Requirements in the Process Industry

In any organization, business case, research, or engineering projects, the people involved have to deal with large amounts of information. This information is then processed into a format suitable for use in making decisions and solving problems [1]. Many research projects have theoretically or empirically established that human brains have limited capacity for information processing [2, 3]. The approximate maximum number of variables that humans can process at any one time is four [2]. Apart from the limited information processing capacity or heavy mental workload, insufficient knowledge is another issue in decision making and problem solving [4]. Therefore, scientists brought computer systems and artificial intelligence such as

various types of decision support systems, supervisory control systems, and expert systems, to aid humans in information processing, decision making and problem solving [1]. Through the cooperation of psychologists and computer scientists, principals from human factors and psychological science were introduced into some of the computer systems to improve their functions [1, 5]. Air traffic control systems represent an example of the success of this [5, 6].

Process control is commonly understood as a statistics and engineering discipline that deals with architectures, mechanisms, and algorithms for controlling the output of a specific process [7]. Digital computer control, which is linked to the availability of computers, was first used in the early 1980s. The aims were and still are to maintain a process operating steadily under the designed specification conditions. To goal is to achieve the desired quality of the product, and reduce cost by through improving the efficiency of the process, while minimizing the human and systems errors that may occur in the process. However the potential to integrate the power of human reasoning and decision making with the almost unlimited computational capacity now available has not been fully explored [8].

The fundamental premise of traditional process control was to remove deviations from the target condition of the process by measuring and acting on single variables, for example, liquid level to control flow, temperature to control energy input [7]. Over time, many compensatory rather than corrective control strategies were applied to any cause that arose or became embedded in the process. This tendency was reinforced by the drive to achieve automatic operation with a minimum of human intervention. However, compensatory actions do not by their nature address the root causes, or trigger subsequent human actions to remove them, so that similar or even more serious variations will occur in the future. Furthermore, many processes are multivariate, with the variables interacting in a very complex manner. Human intervention, diagnosis and decision making are required to identify the root causes, take corrective actions, and thereby improve the process and product quality over time. Decision making in a complex industrial plant involves psychologically related factors such as intuitive reasoning, operator response characteristics, perception of risk, and the implications of rewards. While a significant body of work does exist on decision science, research concerning human interaction with process control systems is still at the development stage.

1.2 Requirements in Aluminium Smelters

Aluminium smelting is a process which is multivariate and involves highly complex mechanisms such as mass and energy balances, electrochemical reactions, the supply of reactants and the maintenance of the composition of the reaction mixture [9]. The large amount of information coming in from such a process, some in real-time and others intermittently at varying frequency, is challenging for a human brain to process. To control this complex process to achieve high productivity and efficiency requires day to day (and sometimes minute to minute) monitoring of the variables, and a high level of deductive problem solving and decision making. Establishing and implementing a computer system for operational staff in a smelter to manage not only the process and maintenance functions, but also the work of people, has stimulated

much interest. Many technical solutions have been proposed, but usually with small incremental improvements.

A few supervisory systems have been built and tested in a number of smelters [10, 11, 12, 13, 14]. The common aim is to collect all the process information and present it in a visual format, hence to help the operational staff understand the process variations better. Some of the supervisory systems incorporated technologies such as fuzzy logics, neural networks, or even more advanced tools such as 3D control envelopes to diagnose any abnormality in the process [13, 15, 17, 18, 19]. The common finding from the evaluation of the efficacy of supervisory systems is that they help the operational staff to achieve better process control [10, 11, 12, 13, 14, 17]. However, these claims are based on the observations of the process control output. The real mechanism of the effectiveness of the supervisory systems on process control remains unexplored. Furthermore, human operators are only considered as the users, while the human reasoning aspect and the interaction with the systems, as well as the other factors such as the impact of organization and management are absent in these explanations.

1.3 Effect of Leadership and Management Style on Decision Making

The quality of the decisions made by managers reflects their effectiveness. However, their leadership and management styles are one of the factors which influence the decision making process. One of the decision making and problem solving models that is widely used in many organizations involves five basic components – problem recognition, information search, construction of alternatives, choice, and implementation [1, 20, 21]. Each step in the decision making process can be affected by environmental and organizational factors, as well as personal values, personality, and the perception of risk, amongst others [20, 22].

In any organization or any cultural work environment, motivation always plays a significant role in governing behaviour and work performance [20, 22]. Job performance has been defined as a function of capacity to perform, opportunity to perform, and willingness to perform [22]. Willingness is effectively associated with motivation. Motivated employees are able to perform better and achieve set goals. The sources of motivation vary with different cultures [20, 23]. Organizations implement a variety of rewards to attract, retain, and motivate people to achieve both personal and organizational goals [22]. Many organizations use money in the form of salary increases or bonuses as a reward to motivate the employees [22, 24, 25]. Maslow's theory of human motivation classified the need of human beings into five hierarchical levels: from physiological, to safety, to social, to esteem, and then to the highest level – self actualization [26]. In certain circumstances, money can help humans to meet the needs of Maslow's first two levels, for example having enough money to buy food or to buy a house.

1.4 Objectives

The present research aims to study human reasoning, decision making, and behaviour with respect to their influence on process control in a complex industrial environment. This will be accomplished through a case study of the implementation of a new supervisory control system. Also included is a series of case studies on operational and process control tasks in

an aluminium smelter. Due to commercial and industrial sensitivity, the smelter where this work is conducted will be referred to as Smelter A. This research work will also investigate any environmental or organizational factors that had an impact on the quality of decisions made. The ultimate aim of this research, therefore, is to meet the requirements of the process industry by incorporating human factors and decision making strategies into computer programs, such as supervisory control systems.

2 A Case Study – Bath Height Control

To facilitate the discussions, some common terms used in the aluminium smelting industry are given here.

Glossary

Anode: The carbon mass connected to the positive side of the power supply and used for the electrochemical removal of oxide ions. The anode is gradually consumed in the electrochemical process and an anode spends about 28 days in the electrolytic cell before it is replaced.

Anode butts: A replaced anode which has been used in an electrolytic cell and has reached the end of its useful life.

Alumina: The reactant in the process which is reduced into aluminium in the electrolysis.

Bath: The molten electrolyte used in the cell.

Bath height: The bath liquid level measurement.

Bath processing: Crust material on anode butts, and tapped bath material (solidified) are crushed into a suitable size for use in covering new anodes in the pots.

Current efficiency: The ratio of the quantity of metal produced in the cell for the number of Coulombs passed compared to that theoretically expected from Faraday's Law. Expressed as a percentage.

Crusher: Machine for crushing solid material.

Cryolite: Electrolyte.

Crushed bath: Solid bath material or solid crust material after passing through the crusher.

Crust: The solidified electrolyte-alumina powder matrix that forms on top of the anodes.

Pot: An expression used for an electrolytic cell.

Potroom: Production hall which contains a number of pots aligned in series.

Potline: A number of pots linked together in series, electrically separate from any other potline.

Pacman material: The material scooped from the surface or bottom of an anode cavity when an anode is removed by a machine commonly referred to as Pacman.

Sludge: The alumina-electrolyte matrix beneath the metal pad. Synonymous with Muck.

Tap: A term used to describe the act of removing bath or metal from a pot.

Section: A group of pots.

Stub: The steel rod that is casted into the anode for electrical contact and physical support.

(Note: definitions are adopted from [39])

2.1 Background

The significance of bath mass balance is reflected through its impact on the mass balance, energy balance, and current efficiency of a pot [27, 28]. Maintaining constant liquid bath volume is important for bath mass balance. Liquid bath volume can be measured by adding and analysing trace elements such as Sr into the bath [17, 29]. However, this procedure is relatively difficult and tedious in practical operation. Instead of controlling bath volume, bath height is measured and monitored every day.

Bath height has a direct impact on current efficiency and other process variables, such as alumina concentration, voltage, and metal purity. When the bath height is low, the retention time is short, and alumina tends to sink to the bottom of the pot before it can dissolve into the bath. Hence the alumina concentration in the bath is low, because the alumina has become part of the sludge formed at the bottom of the pot [17].

With low bath height, there is a potential risk of open circuit. To prevent this situation, anodes have to be lowered, that is the anode – cathode distance is reduced. However, this could result in low bath temperature, sludge formation, and increased bubble noise, as well as back reaction, hence reducing current efficiency [30, 31]. On the other hand, when the bath height exceeds the upper control limit, there is an increased chance for the liquid bath to contact the stubs, and hence increase the iron content in the aluminium metal [32].

Low bath height and large fluctuation situations have been of major concern in Smelter A. Therefore, this case study aims at identifying the variables which are associated with bath height control in Smelter A, and investigating the causes of their bath height control issues. This case study also attempts to connect the human behaviour and reasoning with process control and in this case, bath height control.

2.2 Variables That Affect Bath Height Control

Table 1 lists the factors which might contribute to bath height variation. In this study, these variables are categorized into two groups. One group is referred to as ‘common factors’, which have impact on the entire potline. An example is anode quality. If a common factor has an impact on bath height control, every section in the potline is affected the same way. The other group is referred to as ‘individual factors’. Which have a different impact on different parts of the potline. For example, if there is an effect on bath height control of the management or leadership style of section leaders, then this effect will be different in sections of the potline with different leaders.

2.3 Method

In this study, process data and events were collected from four sections in Smelter A as shown in Figure 1. Statistical analysis of the process data will provide some evidence to confirm the effect of the variables on bath height control. Evaluating the pot performance and the operating conditions in the potrooms, and working with the operators and section leaders, provided an opportunity to observe their modus operandi, and responses to operational problems, and work practices.

Table 1. Categorization of possible bath height control variables

Common Factors	Individual Factors
Availability of crushed bath	Metal height
Power interruption	Voltage control
Anode quality	Making different decisions
Cast house machine working condition	Section leader's Management/Leadership style
Implementation of Information Technology such as supervisory control systems	Degree of applying Information Technology such as supervisory control systems
Work practice standards	Degree of implementing Reward and Punishment system
Implementation of Reward and Punishment system	Degree of implementing correct work practices

Fig. 1. A schematic drawing illustrating the layout of the four sections in Smelter A

A survey, with 21 questions, was designed to obtain information that will help with the understanding of how bath height control is being carried out in Smelter A. The survey also provided information to investigate the dominant factors that resulted in low bath height, as observed in March, June, August, and October in 2008. The participants were 6 section leaders, 5 vice section leaders, 10 shift section leaders, 2 potroom managers, and 1 engineer. An interview with one of the section leaders who was regarded as a role model by the smelter managers, provided a detailed insight into the bath height control situation in Smelter A.

3 Results and Discussions

3.1 The Effect of the Availability of Crushed Material

In the bath processing and recycling circuit, tapped solid bath material, crust material from anode butts, and pacman material are crushed into particles with a size range of 100µm to 10mm [33]. The crushed material is used mainly to cover newly set anodes or to re-dress the exposed anodes. This serves to prevent oxidation of the anodes and regulate the heat balance of the pot. The material which falls into the pot cavity during anode changing, dressing, or re-dressing, becomes one of the sources to replenish liquid bath [28, 33, 34].

Figure 2 shows the daily average of bath height measurements of the four sections in two potrooms from March to October 2008. As indicated in Figure 2, the targeted bath height measurement (cl) is 19 cm, the upper control limit (ucl) is 23 cm, and the lower control limit (lcl) is 15 cm. Also, the upper warning limit (uwl) and the lower

Fig. 2. Bath height measurements of the four sections from March to October 2008 (Y-axis: Bath height in cm)

Fig. 3. Bath height measurements for each section when crushed bath was not available – 15/05/2008 to 15/06/2008 (Y-axis: Bath height in cm)

warning limit (lwl) are 21 and 17 cm respectively. According to the operational staff, the crusher was broken at a rate of once every 2 weeks from March to May and from July to August. From the middle of May to the middle of June (Period A in Figure 2), the crusher was completely out of action. It was out of action again from September to the end of October (Period B in Figure 2). Periods A and B in Figure 2 correspond to periods when the crusher was broken for more than 10 days, and consequently crushed bath was unavailable.

Figure 2 also shows that the average bath height of the four sections decreased when the crushed bath was unavailable for a long period of time (in both Period A and B). Figure 3 shows the bath height measurements for each section when the crusher was broken in Period A. All the pots were operating in a low bath height condition. Sections 1, 2, and 3 were operating below the lower control limits for most

of the time. Section 4 operated within the control band, but bath height was below the lower warning limit for the majority of the time. These data show clearly that bath height has a strong relationship with the availability of crushed bath.

3.2 The Effect of the Supervisory Control System

Smelter A implemented a newly designed supervisory control system in July 2008. This system is able to warn the user when a process parameter is out of control by use of a visual display, incorporating elements such as colour and statistical graphs. For example, when a bath height measurement of a pot is below the lower control limit or above the upper control limit, the pot will be highlighted in red on the user interface. This is one of the concepts applied to alarm alerting systems, which is adopted from the human factors engineering literature [35]. The outcome on bath height control by using the colour alarm system in the supervisory control system is presented below.

Figure 4 shows the daily average of the four sections for bath height measurements in Period C (before SCS implementation) and Period D (after SCS implementation). They show the overall trends of bath height measurement of the four sections. The average bath height in Period C had a large variation, whereas that in Period D was more constant. This illustrates the effectiveness of the use of supervisory control system. The data in Figure 4 have the standard deviations of the bath height measurements are 2.33 and 1.79 before and after implementing the supervisory control system. A sign test, which is commonly used to test the assumption that there is ‘no difference’ between the continuous distributions of two variables, confirmed the statistical significance of the difference in bath height measurements in Period C and Period D ($p = 0.0136$). However, to determine that this difference was caused by the implementation of the colour alarm in the supervisory control system, further explanations were searched for through surveys and interviews.

Findings from the survey and interviews with the section leaders in Smelter A revealed that the Red colour alarms used to indicate low bath height gave adequate warning of the process state and put pressure on them to correct the problem. If the bath height was out of control, the section leaders would feel responsible for poor operation and face punishment from managers. Therefore, when red colour alarms were shown on the user interface, the section leader would first confirm the situation by searching for more information from both the supervisory control system and the operators, and then instruct the operators to take appropriate action to fix the problem.

Fig. 4. Bath height measurements for the four sections before (Period C in Figure 2) and after (Period D in Figure 2) implementing the supervisory control system (SCS) - (Y-axis: Bath height in cm)

Some section leaders have set an allowable number of red colour alarms in their control plans. From observation, the 'red colour alarm' has been frequently used in their communication language. This indicates that the colour alarms in the supervisory control system have a positive impact on bath height control. The impact of the other common factors was not investigated in this case study. Future investigations are required to confirm their effects on bath height control.

3.3 The Effects of 'Individual Factors'

The data in Figure 3 indicate that bath height measurements for Section 4 are closer to the target than those of the other three sections when the crusher was broken. To confirm this observation, a sign test was carried out. Very small p-values, much lower than 0.001, were obtained from the comparisons between Sections 4 and 1, Sections 4 and 2, and Sections 4 and 3. They indicate that the bath height measurements for Section 4 are highly significantly different from the measurements for any of the other three sections. Observation of the process data and other events suggested that the difference in bath height measurements between Section 4 and the other three sections is due to individual factors.

In the situation when the crusher was out of action, most of the section leaders would add cryolite into the pots which had low bath height, or they would not take any action. The Section 4 leader took a different approach from that of the others. He instructed the operators to tap out liquid bath from pots that had excess liquid bath into trays. The cool solidified tapped-out bath was broken into large pieces and stored away. When the crushed bath material was not available, this section leader would ask the operators to break the large lumps of the stocked bath using hammers, and then feed these into those pots with low bath height, or use it as anode cover material. This approach led to better bath height control results, which are clearly shown in the graphs in Figures 3.

3.4 The Effects of Leadership and Management Style

Motivation

In Smelter A, a reward system was used to motivate and manage the operational staff. Staff performance was assessed by the immediate supervisor. The smelter manager, potline manager, and potroom managers all agreed that the Section 4 leader is a competent and effective leader. He understands and has the ability to control the process. He also has motivation to constantly seek improvement. This section leader has been rewarded and taken as a role model for the other co-workers. The recognition and rewards from the superiors have greatly motivated this section leader.

A reward system was implemented in every section to assist the section leader to manage the operational teams. As an effective leader, the Section 4 leader tested and modified the reward system in his section. It was recognized by the managers that the modified system is more effective and it has been decided that it will replace the original system in the other sections. In the modified system, the Section 4 leader delegated a person to manage the reward system in his section full time. This person is responsible for checking and recording the work quality of the operators. He rewards the operators for outstanding jobs performed by giving extra points which

contribute to a salary increase. If any poor quality work is found, he informs the responsible operator to fix the problems. If the quality remains poor, he deducts points (i.e., reducing salary) from the operator concerned. This new system increases the degree of supervision by having a full time person assessing the work performance of the operators. It also provides a second chance for the operators to improve their work quality if it was not up to standard in the first assessment. This modified system has been shown to be effective through the operational and process control outcomes.

Money as a reward to motivate the operators in Smelter A has had a positive impact, and has been demonstrated by Section 4's operational achievement. This can be explained suitably by Maslow's theory. Because Smelter A is situated in a developing area where people have various educational backgrounds, and especially different financial situations, a large number of operators are working to secure the needs specified by Maslow's first two levels. These needs are related to physiological and safety, which money is able to satisfy for most people.

Decision making

The Section 4 leader is a motivated leader who is also able to motivate the operators to achieve positive results. Motivation is often associated with creative thinking and proactivity [36, 37, 38]. These can often be reflected through decisions made to solve a problem or the quality of a task performed [1, 38]. Specific questions were designed to understand how the operational staff in Smelter A made decisions to solve the bath height control problems. Most of the section leaders recognized low bath height situations by reading tabulated data reports and attending to the 'red' warning alarms in the new supervisory control system. Most of them would search for more information to firstly confirm the situation, and then try to understand and investigate the cause of the low bath height. When crusher breakdown was the root cause of low bath height, most of the section leaders considered this to be a cause that was not under their control, and therefore no further action was taken. However, the approach of the leader of Section 4 of reusing excess bath (by tapping out and stockpiling) was a creative solution to fix and prevent low bath height situations.

4 Conclusions

This on-site study was accomplished by analysing the process data, surveys, interview information, and observations in Smelter A. The main findings from this case study are:

1. Crusher breakdown caused crushed bath material to be unavailable, and was the main root cause of the low bath height situation,
2. The 'red' colour alarms in the supervisory control system increased the operational staff's awareness of the process situation, especially regarding the low bath height situation,
3. Money as reward in Section 4 had positive impacts on bath height control,
4. Leadership and management styles had an impact on employee's motivation, creativity, and decision making.

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