1.8. Complexity Science

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1.8. Complexity Science

In this chapter, a scoping of complexity science and its relationship to safety engagement in the mining industry is described. We found five case studies, 1 qualitative study, 1 randomized controlled trial and 1 controlled trial, 11 theoretical papers, and 1 quality improvement project. Complex adaptive systems are defined as groups of individuals, or systems, co-existing interdependently, interacting with each other and with the external environment in ways that are interconnected, unpredictable and potentially extensive. The results of these interactions are difficult to control but at the same time, the outcomes may be rich, inventive, and robust (Hast et al., 2013). The main characteristics of complex adaptive systems are interconnectedness, self-organization, emergence, and coevolution (McDaniel & Driebe, 2001).

Complexity theory is a theory that attempts to explain the complex behaviors that emerge as a result of interactions between dynamic systems. All of the involved systems have their own specific culture as well as comprising heterogeneous personalities. Complexity theory evolved from a combination of comparable theories from the sciences, one of which was chaos theory (Chaffee & McNeill, 2007). Chaos theory is a theory describing the multiplying effect of initial changes on dynamic systems; however, these effects can be calculated in order to predict the outcomes. The underlying principle is that order underlies and emerges from apparent disorder (Haigh, 2002; Davidson, Ray & Turkel, 2011).

Complexity science is a perspective serving to explain relationships and the unpredictable behaviors that results from the interactions between interdependent and evolving systems. A key concept of complexity science is that systems will adapt and evolve into new systems over time (Chaffee & McNeill, 2007; Davidson, Ray & Turkel, 2011). Complexity science and complexity theory are often used interchangeably.

The question that guided our search was “How does complexity science explain safety engagement in the mining community?”

Method

A scoping review of the literature was undertaken using a formal and informal search. The initial formal search was conducted using the following key words:

1. Miners (Miners OR “resource extraction” OR workers OR employees OR “mining industry” OR “mining community” OR mines OR “mineral resources”) and,
2. Complexity theory (“complexity theory” OR “complexity science” OR “chaos theory”)
3. Safety Engagement (or “risk taking behavior” OR “risk taking behaviour” OR ”safety behavior” OR “safety behaviour” OR safety OR “high risk behavior” OR “high risk behaviour” OR Safety engagement” OR “safety rule violation” OR “accident proneness” OR “risk perception” OR “perception of safety” OR “safety devices” OR “workplace safety” OR “work safety” OR “risk tolerance”)

Search Strategy. The databases searched are listed in the results. From this search, we selected articles based on the inclusion/exclusion criteria. The inclusion and exclusion criteria were kept broad in that we did not specify the types of research methods to be included or excluded in order to capture as many research articles on the topic as possible. In our search, we collected articles that were pertinent in this topic area. The broad inclusion and exclusion criteria allowed us to explore the literature in this area more completely. An exception to the inclusion/exclusion criteria is an article deemed to be a seminal article in complexity science was included in the review even though it was older than five years: McDaniel et al. (1997).

Table 1. Complexity Science Inclusion/Exclusion Criteria for Article Selection

Inclusion Criteria	Exclusion Criteria
• Articles with key terms in the title or abstract	• Editorials
• Peer reviewed	• Commentaries
• Within 5 years	• Book reviews
• English language articles	

Screening Strategy. The articles were checked for inclusion by two team members. The inclusion process was iterative in that the included/excluded articles were reviewed again for inclusion as the themes were developing. The team had final approval of the included articles. Those not applicable to the scoping review were excluded.

Results

A brief summary of each article including its location, population studied, main issue addressed, comparison group, and primary outcomes is provided in Appendix G. Table 2 is an overview of the scope of the review and articles identified.

Table 2. Complexity Science Databases searched

Database	No of articles found from search	Articles Selected for Review	Final article selection
Academic Search Complete	15	70	24
ERIC	3		
Nursing and Allied Health	19		
Embase	1		
Scopus	7		
Joanna Briggs	0		
ProQuest	13		
Medline	12		

Description of Included Articles. Table 3 provides an overview of the types of publications, country of publication, and populations studied.

Table 3. Complexity Science: Population, Country of Research, and Type of Study

Type of Study	Country of Research	Population
Quantitative studies: • One controlled trial • One randomized trial	USA (4) Canada (1) UK (3)	Organizations (general) (6) Health care (4) Workers (general) (2)

Qualitative studies: • One focus group/interviews • Five case studies Other: • 11 theoretical articles • One quality improvement project	Austria (1)	Communities (1) Risk management (1) Exploration (1) Emergency services (1) Education (1)

Description of Identified Factors. In order to make it easier to describe the results of the scoping review, the articles were divided into six conceptual categories: complex adaptive systems, self-organization, patterns of interactions and connections, early warning signs (weak signals), unpredictability/uncertainty, ripple effect – small changes can lead to big payoffs or challenges, and change/implementation strategy.

Complex adaptive systems. There were four articles found which addressed complex adaptive systems. Reiman, Rollenhagen, Pietikainen, and Heillila (2015) developed a framework for safety management based upon the literature on complex adaptive systems, safety management, and empirical findings on safety management in the nuclear power and health fields. They determined organizations to be complex adaptive systems with seven key features: non-linearity, emergence, self-organization, far-from-equilibrium-conditions, coevolution, nested systems and history-dependence; and, as a result safety was deemed to be emergent. According to Reiman et al., traditional leadership theory has limitations in managing complex systems and should be complemented and informed by approaches from complexity theory. The authors arrived at eight principles of adaptive safety management: promote safety as a shared guiding principle, optimize local efficiency, facilitate interaction and build connections, set objectives and prioritize, facilitate novelty and diversity, monitor system activities and boundaries, create capability for situational self-organizing, define system boundaries, and standardize activities.

Three articles described organizations as complex adaptive systems. Complexity science contributes to the understanding of the relationship between leadership approach and organizational performance (Nienaber & Svensson, 2013). In the traditional linear top down approach, senior leadership (CEO's and top managers) take credit for organizational performance and growth which is usually defined financially (and do not necessarily take responsibility for failures). The three groups of employees, senior leadership, middle management and front line workers, have different roles and tasks that determine the leadership approach. Senior leadership make decisions that are future based by setting goals and providing strategies to meet them, ensuring that needed resources are in place, operating from what is deemed a rationalist approach. Middle management makes decisions that are past-based, ensuring that the goals and strategies are put into action and have good understanding of the internal and external environment. Front line workers operationalize the goals and are present based. The authors argue that the traditional leadership approach does not accurately represent nature of an organization where tasks and roles overlap and interaction in an organization as linear, non- linear and even random (Nienaber & Svensson, 2013). Complexity science more accurately represents leadership and management taking formative and transformative approaches as well as rationalist. All levels of employees in the organization would take a pluralistic approach and everyone's contribution to organizational performance is acknowledged.

The use of a complexity science mathematical model to represent organizations makes sense since organizations rely largely on human resources to help with achieving operational goals**;** and because human beings think and act based on previous experiences, any event that may affect their working environment will be questioned (Allen, 2013; Allen, 2014). "Complex systems thinking offers us an integrative paradigm in which we retain the fact of multiple subjectivities, differing perceptions and views, and indeed see this as part of the complexity, as a source of creative interactions and of innovation and change" (p. 714, Allen, 2013).

Allen (2014) maintained that "there are multiple understandings, values, goals and behaviors that co-habit a complex system at any moment, and these change with the nature of the elements in interaction as well as with their changing interpretive frameworks of what is going on" (p. 287). As well, he emphasized that "there is no scientific, unique way to change our beliefs. In reality, we simply have to experiment with modified views and try to see whether the new system seems to work 'better' than the old" (Allen, p. 285, 2014). Therefore, maintaining a safety culture is possible only insofar as it is perceived to be of high importance to individual miners, as well as management. According to Allen (2014), decisions and policies that are made are only good for the immediate and near future time frames because "complexity tells us that our understanding of the system may be good for the short term, reasonable for the medium but will inevitably be inadequate for the long" (Allen, p. 287, 2014). Therefore, emerging behaviors will need to be monitored so that organizations can adapt to new innovations, technologies, perceptions and views, and creative interactions (Allen 2014).

Self-organization. Four articles discussed the concept of self-organization. In a discussion paper, Menin (2010) stated that creating conditions for self-organization should increase interactions, resulting in new knowledge emerging. However, it is not just about putting people in proximity of each other for this to occur; to destabilize the status quo, the interactions need to be of quality with multiple opportunities for interaction and feedback (Menin, 2010). McDaniel (1997) noted that systems are unpredictable on how they will react to stimuli, but they will always self-organize, therefore connections and relationships are key. If relationships and connections are weak, valuable resources may be unknown across organizations; therefore, strengthening internal organization cooperation structures are important to reduce error and build buy in and capacity (Kremser 2011). Kremser found that where loose organizational associations exist, high quality individual education must exist at all levels; and incentive schemes do not work long term unless there is internal buy in. Behavior on the job and off may differ due to organizational rules and subculture (Kremser, 2011).

In a case study of the community of Camborne, West Cornwall, Durie and Wyatt (2013) looked at the impact of a community improvement project. They attributed the success of the project to complexity theory and an asset-based model of health improvement. They determined problems and solutions should come from the community, non-linear relationships were evident in the design and delivery of the project, members of the community and service providers adapted and evolved together, and leaders emerged from within the community, thus demonstrating the self-organizational characteristic of complexity theory.

Simpson et al. (2013) used complexity science principles to develop a process to identify and assess challenges and solutions when implementing 2 complex multicomponent organizational interventions to reduce falls in nursing homes. Besides the interventions there were two additional sources or types of complexity, the sites and the research team. There was a need to maintain some flexibility in the implementation because of the complexities, but there was also a need to maintain integrity of the research. Simpson et al. developed a process to protect research integrity that became the Tool for Evaluating Research Implementation Challenges (TECH), a systematic way of identifying, assessing and addressing challenges, through questioning and dialogue among team members. Any implementation changes were documented.

Patterns of interactions and connections. Eight articles provided information about patterns of interactions and connections. These articles described interactions and relationships. In his seminal article, McDaniel et al (1997) stated connections and relationships are key in order for employees to learn to value diverse opinions. Hast, DiGiola, Thompson, and Wolf (2013) looked at improved patient and family centered care by the incorporation of a 6-step patient and family-centered care methodology. They used complexity science to drive organizational quality improvement change by studying the connections in place and ongoing patterns of interactions through flow mapping, patient shadowing, and focus groups. Menin (2010) noted it is important for quality interactions to have multiple interactions with short loop feedback. The author suggested organizations that have fuzzy boundaries have increased interactions.

Complexity management theory draws on the principles of complexity science and "moves from systems to human interaction as the primary actor in complexity" and that outcomes are influenced by (a) the human tendency for self-interest and relating everything to their own experience, (b) conversations that shape people's understanding of what is true and what is appropriate action…and (c) the radical unpredictability of the direction in which connections and relationships evolve (Carillo, 2011, p. 294). Carillo (2012) believed designing our training, education, and communication forums to fit the way people understand and solve problems could be what leads to the next level of safety excellence. In a subsequent article, Carrillo (2012) described a relationship-based change model in which relationship building increases trust thus impacting safety. In this model, safety is sustained within the relationships through social interaction and a trusting environment. Through complexity science theory, control is taken away from management and given to employees through awareness, continuous learning, and adaptation (Carillo, 2012). Kremser (2011) stated a system's internal structures were more important than its external framework when considering reactions to an intervention.

One article described the importance of considering relationships. Carrillo (2012) reported relationship building increases trust and the *Relationship-Based Change Model* encompasses strategies to effect this. Carrillo also found that when studying disasters, it was apparent that management should use tools to leverage human capability and social interaction in order to identify safety problems early. *Complexity Management Theory s*witches from control by management to awareness, continuous learning and adaptation by employees.

One article gave an example of relationships and uncertainty, and how leadership impacts both. Through a case example, Lee (2011) illustrated uncertainty must be met with purposeful and informed leadership and change strategies. The author suggested positive change requires organizational alignment as a standard leadership skill and practice; and change levers such as culture, social networks, and strategy are strongest and often outside a manager's span of control. Lee reported peer safety behavior may be governed by the fear of losing social standing; and workers are naturally competitive and will compete for numbers of safety days or care of team health. Therefore, aligning internal and external challenges and opportunities determines a company's long-term success or failure.

Addressing the need for creating a culture of safety, Carillo (2011) discussed the significance of sense-making and polarity. She emphasized the importance of the communication that must occur within organizations. In addition, she introduced the theory of complexity management which is an area of research focusing on understanding the development of safety performance and the human factors that can influence it. Carillo described sensemaking as the process taken by individuals as they attempt to make meaning of their experiences based on their understanding of the context they are in currently: and "sensemaking is related to the concept of 'safety culture' in that it embraces the human propensity to form norms and assumptions around the right way to do things" (p. 294). Polarity, as part of sensemaking, refers to conflicting priorities between the different stakeholders that are inherent in all organizations; however, in the best interest of the organization, conflicting objectives of management and employees must be managed and met as much as possible (Carrillo, 2011). For many organizations, and in particular the mining industry, protecting the safety of the workers is the responsibility of employees and management together. Therefore, respectful listening and constant communication are essential to achieve this goal. Specifically, with respect to establishing a safety culture, Carillo believed that "relationship building and sensemaking are management tools to help people arrive at common sense of tough questions like 'What does safe look like?' 'What is acceptable risk?' or 'Why should I change the way I've always done it if I've never gotten hurt?'" (p. 295).

Early warning signs (weak signals). Three articles related to early warning signs or weak signals. In a seminal article describing complexity science, McDaniel (1997) stated before any intrinsic change or challenge, there were usually early warning signs that may be small and dismissed out of hand. Leaders must be careful observers and watchful for these "weak signals "(McDaniel 1997). Not only are these signs early indications of positive change, but they can also signal challenges. In an analysis of accident causes, Kontogiannis and Malakis (2012) found that weak signals of impending accidents are often ignored and stressed that organizations need to be vigilant by examining near misses and reinforcing loops that lead to accidents; thus avoiding repeat accidents. They advocated the use of a *Systems Theoretic Accident Model and Process* (STAMP) and *Viable Systems Model* (VSM) framework to decrease accidents by focusing on the interactions between different levels in a socio-technical system, and by looking for flaws in control processes as well as constraints throughout the system. The key concept of the VSM framework is how organizations handle the complexity of both their environment and of their own activities, which is vital for ongoing organizational viability (Kontagiannis & Malakis, 2012). Kontagiannis and Malakis (2012) stated one must look at the global structure of an organization, not the single event, and avoid overreliance on single sources of information. However, McDaniel (1997) stated the capacity to learn from a single event is crucial, as well as focusing on the needs of an organization plus interactions in a social technical system (information channels). How organizations respond to adverse events is worthy of study in order to improve.

In a case study, Gifun and Karydas (2010) found disruptions are almost never the result of a single failure and large scale disruptions are usually the result of the confluence of several factors. They reported although many signs may indicate a disruption is imminent, these signs are often ignored; and to mitigate consequences, organizations should take preemptive action to reduce severity. Gifun and Karydas described a highly reliable resilient complex organization (HRRO) as the ability to anticipate, resist, and recover from disasters; and the model is testable and generalizable across different organizations and cultures. The authors further described the organizational attributes of HRRO's as those which optimize the balance of complexity and simplicity. Several concepts applied by the authors are the complex system which recognizes unpredictability, the analytic deliberative process which assesses vulnerability, the multi-criteria decisions which formally draw multiple perspectives and evaluations into a decision-making process, and the analytic hierarchy process which determines the weights of each criterion in comparison with all others.

Unpredictability/uncertainty. Three articles were related to unpredictability or uncertainty. McDaniel (1997) found that the future cannot be precisely predicted due to the combination of many known and unknown variables at play. McDaniel stated that change is not totally random, and the property of self-organization is a fundamental quantum principle that can be capitalized on. However, he suggested other tenets of complexity theory should be understood in order to plan strategies, and the focus should be on short term rather than long term goals.

Grote (2015) maintained that uncertainty needs to be acknowledged and managed as part of risk assessment and risk management. Different organizations and different operations within an organization call for different ways of managing uncertainty, namely reducing, maintaining or increasing it. Increasing uncertainty is rooted conceptually in complexity science. All three are necessary to maintain a 'balance between stability and flexibility' with an appropriate 'match between control and accountability'. An increase in uncertainty has an inverse relationship with stability and control but is necessary when flexibility and innovation will contribute to better risk management.

Desai (2010) addressed the inclusion of many stakeholders such as owners, employees, suppliers, partners, and customers in organizational discussions. He used insights gained from complexity science to discuss the importance of including all stakeholders in order to keep organizations up to date and innovative.

Ripple effect. Four articles related to the ripple effect. McDaniel (1997) found that small changes can lead to big payoffs or challenges within an organization. His recommendation was that organizations should not underestimate the effect of a small change on the system at large. Goh et al (2012) reviewed the concept of system dynamics to analyze accident prevention. They discussed the incorporation of a *causal loop tool* used by Australian mining employees themselves to diagnosis issues/variables and develop solutions to decrease disabling injury frequency; a concept map per se of the feedback loops and interactions between variables would elicit the deep individual knowledge of the miners to develop. Hast et al (2013) found that quality improvements in family- and patient-centered care were optimized when co-designed by participants.

Lesch et al (2012) measured comprehension of warning symbol signage between younger and older adults before and after training. The authors found that to optimize comprehension by older adults, symbols should be less complex, have a clear relationship to a real-world reference and incorporate cues to knowledge for linking new knowledge to long-term memory.

Change/implementation strategy. One article discussed change and implementation strategies in detail. Successful implementation of safety practices depends on identification of factors which hinders or assists with the process. A study was undertaken by Ball, Wilcock, and Aung (2009) in which employees from five meat processing plants were interviewed to determine factors that influenced the implementation process of food safety practices at the plants. While the focus of their study was on food safety, the results can still be compared to the implementation of safety practices within the mining industry. Factors influencing the implementation process identified in the study are: facilities and equipment; training and feedback; management commitment; approach to integration; employee characteristics; execution of safety practices; and external factors (Ball et al. 2009). Many of these factors are self-explanatory in their ability to assist in, or hinder, the implementation process regardless of the organization or industry. However, it is worthwhile to further discuss a few of the factors.

Ball et al. (2009) found training to be critical as it "provides employees with the skills and knowledge they need to do their jobs" (p. 208). The authors made a distinction between skills and knowledge with skill being defined as the "ability to do something" and knowledge as having "an understanding how why one would do something" (p. 209). This is an important distinction as understanding the rationale behind practices often leads to an increased compliance with safety practices or procedures. A surprising finding of the study was the "general agreement among respondents that positive feedback about performance was important reinforcement" (p. 208). Therefore, when new practices were introduced and implemented, it was recommended that management take the time to acknowledge employees' persistence with the new practice(s).

Other influences affecting the implementation process were approach to integration, execution of safety practices, and external factors. Interviews done by Ball et al. (2009) demonstrated that a more gradual approach to the new practices was more likely to lead to a successful implementation; and this depended upon the reasons for the introduction of new safety practices and which needed to be considered on an individual basis. They referred to the concept of execution of safety practices as "the following through on and recording of food safety practices" (p. 210) because documentation, particularly when it was accompanied by signage of employees, increased accountability, and stronger adherence to policies and procedures. Ball et al. found external factors such as government regulations should have had a direct effect on successful implementation of new safety policies; however, there was still a possibility of employees circumventing new practices and defaulting to previously adopted ones. Ultimately, changes needed to make sense to people before an amendment to practice was adopted, as suggested by Carillo (2011). That being said, the success of any implementation process depends on the interplay of the factors previously discussed.

Discussion

This scoping review looked at the influence of complexity science on the safety engagement of miners. A seminal article was included in this scoping review. McDaniel (1997) identified the primary principles of complexity science and complex adaptive systems; these principles were supported throughout the articles included in this scoping review. Complexity tenets that were linked to positive safety outcomes were organizations that had non-linear, interactive organizational structures that allowed and encouraged self-organization and engagement between all levels of employees. This enhancement of relationships promoted innovation, leadership, upstream solutions, a respect for diversity and early identification of safety issues. Overall resulting in healthy adaptive organizations in which all employees' shared common purpose and co-evolved in response to changing contexts.

Gaps in the Literature. While the chosen articles in this scoping review did not specifically address the question of "how does complexity science explain safety engagement in the mining community", they do highlight the appropriateness of applying complexity science theory to the analysis of organizational processes. McDaniel (1997) stressed the benefit of using complexity science to inform strategic leadership. Carillo (2011) discussed the importance of relationships and communication within and across all organizational levels. Allen (2013, 2014) emphasized the importance of collaboration and the contribution to innovation, quality improvement which, in the long run will influence the longevity of any organization. While there were numerous articles on complexity science as it relates to organizational dynamics and behavior and there has been research on safety behavior itself, there is a paucity of articles regarding the relevancy of complexity science with respect to the development and sustainment of safety engagement behavior. In their article, Goh et al. (2010) discussed the usefulness of systems thinking when reviewing major environmental disasters that had occurred in the past. Grote (2015) made the recommendation that risks are better managed by creating uncertainty; the reason for this is that workers therefore will not have the opportunity to become complacent. This is reinforced by Carillo's concept of "practical drift" in which workers deviates from the correct procedural processes over time due to the lack of consequences from the departure from following proper processes (2011). The role and responsibilities of leadership have been addressed by some of the articles as well (Carillo, 2011; Reiman et al., 2015; Desai, 2010). However, more research into complexity informing safety engagement needs to be done. The research projects that were introduced in some of the articles need to be developed into quantitative projects in order to provide longitudinal and cross-sectional data, to provide generalizable results.

Recommendations. Recognizing complexity science as an important concept in safety engagement may help to discern future behaviors in organizations that, as complex adaptive systems, are dynamic, unpredictable, and evolving. The following recommendations for industry came out of the scoping review:

- Create an environment that promotes situational self-organizing social networks across the organization and with external stakeholders, while concurrently strengthening all formal organizational cooperation structures.
- Acknowledge all positive contributions to organizational performance.
- Facilitate the participation of all members of the organization in goal setting.
- Plan strategies with a greater focus on short term rather than long term goals.

- Facilitate risk assessment and management processes that balance stability and flexibility.
- Study every safety incident but also be vigilant for early warning signs and near misses that may impact safety. Study the structural loops that may have reinforced them. Involve the participants in this review and promote respectful efficient feedback loops for all members.
- Acknowledge and promote that small changes can lead to big payoffs.
- Involve participants with updating system design/processes/policy.
- Involve participants and design training education, and communication forums to fit the way people understand and solve problems (i.e. link new knowledge to long-term memory for older workers).
- Provide employees with skills and knowledge to do their jobs. Skills were defined as the ability to do something, while knowledge was the understanding of how and why it is done.
- Use a gradual approach to implement new practices. Attention to sense making
- Require employee signage on safety practices .

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