System Dynamics Analysis of Organizational Accidents: A Review of Current Approaches

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Abstract

Organizational accidents are increasingly being studied using system dynamics (SD) tools. However, as compared to social research of organizational accidents, most of the SD studies conducted so far lack grounding in actual data. Ironically, organizational accidents usually have available data in the form of inquiry reports and other public reports. This study reviews SD studies of organizational accidents and proposes ways to improve the rigor of SD analysis of organizational accidents. Eight relevant papers were identified and classified into two broad types: (1) practice-to-theorizing and (2) theorizing-to-practice. Practice-to-theorizing refers to deriving theories from analysis of actual organizational accidents, while theorizing-to-practice refers to use of pre-conceived theoretical model for research. The study found that both approaches can be improved through textual analysis techniques. The paper proposed data analysis procedures to improve robustness of SD analysis of organizational accidents.

Keywords: organizational accidents, coding, social research, methods, causal loop, simulation, system dynamics.

Introduction

Organizational accidents are rare but catastrophic events (Reason 1997). In comparison to individual accidents, organizational accidents involve complex organizational behavior typically beyond the control of accident victims. One of the recent organizational accidents occurred in 2005 in BP Texas City Refinery. The fire and explosion killed 15 people, injured 180 and caused financial losses exceeding US$1.5 billion (Baker 2007; Chemical Safety Board 2007). Other examples of organizational accidents include the

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Westray coal mine explosion in Canada (Hynes and Prasad 1997), the Nicoll Highway collapse in Singapore (Magnus 2005), the Columbia and Challenger space shuttle tragedies (Hall 2003) and the Moura mine explosion in Queensland, Australia (Hopkins 1999). As in the case of BP Texas fire and explosion, not only do these organizational accidents cause loss of precious lives, they lead to huge commercial impacts on the organizations involved and society as a whole.

Perrow (1999) found that interactive complexity and tight coupling of system components make organizational accidents a "normal" occurrence of high technology systems. Perrow (1999) measured interactive complexity based on the number of ways system components can interact and tightness of coupling is measured based on the responsiveness of system components to a change in the system. Other researchers also identified that organizational accidents have long "incubation" period (Vaughan 1996; Turner and Pidgeon 1997; Laugé, Sarriegi, and Torres 2009) and the escalation are not always easily observed. Due to the characteristics of organizational accidents, Goh, Brown and Spickett (2010) suggested that traditional accident investigation tools (Sklet 2004) should be complemented by system dynamics tools to reveal the systemic structure associated with the organizational accident.

In recent years, there has been several system dynamics analysis of organizational accidents. However, the methods used are not consistent. Some placed more emphasis on qualitative system dynamics tools (Goh, Brown, and Spickett 2010; Leveson 2010; Marais, Saleh, and Leveson 2006) and others focus on the stock and flow simulation (Cooke 2003; Cooke and Rohleder 2006; Rudolph and Repenning 2002; Salge and Milling 2006). In comparison with traditional organizational accident research, which usually rely on textual analysis to elicit evidence to support theories on accident causation (e.g. Gephart 1993; Hynes and Prasad 1997), system dynamics analysis of organizational accidents is a departure from the usual. In response to Kopainsky and Luna-Reyes's (2008) recommendation for system dynamics research to integrate social research methods, this paper reviews the current system dynamics approaches used to analyze organizational accident to provide recommendations for methodological improvements. The recommendations will help to establish system dynamics tools as an important supplement to current organizational accident methodologies.

Overview of SD Literature on Organizational Accidents

Table 1 summarizes eight relevant SD literature identified through the web of knowledge research database (Thomson Reuters 2010) and the online proceedings of the International System Dynamics Conference (System Dynamics Society 2010) using different permutations of search terms such as “organizational accident”, “crisis”, “disaster”, “emergency”, “major accident”, “systems thinking, “system dynamics”, “causal loop”, “stock and flow” and “simulation”. The author-date citations, article titles, tools used, research aims and a brief description of the methods are presented in Table 1. Papers that discussed application of system dynamics tools in a generic sense without any collection of empirical data or modeling are excluded in this review.

Table 1 Summary of relevant SD literature on organizational accidents

Author-Date	Title	Tool	Aim	Methods Description
(Tsuchiya et al. 2001)	An analysis of Tokaimura nuclear criticality Accident: A systems approach	Influence diagram/root cause analysis	“… partial root cause analysis of the event using a systems approach”	Qualitative; case specific analysis; single case
(Rudolph and Repenning 2002)	Disaster dynamics: Understanding the role of quantity in organizational collapse.	Stock and flow simulation	“… develop a general theory of how an organizational system responds to an on-going stream of non-novel interruptions to existing plans and procedures”	Simulation; theory based on literature/ case
(Cooke 2003)	A system dynamics analysis of the Westray mine disaster	Causal loop diagram and stock and flow simulation	“… use a simplified model of the Westray mine system to illustrate how the methodology of system dynamics can be useful for understanding the behaviors of complex safety systems…”	Simulation; case specific; single case
(Cooke and Rohleder 2006)	Learning from incidents: from normal accidents to high reliability	Stock and flow simulation	“…to provide a theoretical basis for incident learning systems and provide motivation for managers to consider	Simulation; model based on literature

Author-Date	Title	Tool	Aim	Methods Description
			their implementation."	
(Marais, Saleh, and Leveson 2006)	Archetypes for organizational safety	Archetypes (causal loop diagrams)	"…propose an initial set of six system safety archetypes that model common dynamic organizational behaviors that often lead to accidents"	Qualitative; archetypes
(Salge and Milling 2006)	Who is to blame, the operator or the designer? Two stages of human failure in the Chernobyl accident	Causal loop diagram and stock and flow simulation	"This paper analyses the causes of the Chernobyl power plant accident…"	Simulation; case specific; single case; two separate simulation models used
(Laugé, Sarriegi, and Torres 2009)	The dynamics of crisis lifecycle for emergency management	Qualitative analysis of reference modes	" … to identify the characteristics of each phase by analyzing real cases through the development of reference modes"	Qualitative; reference modes; multiple cases
(Goh, Brown, and Spickett 2010)	Applying systems thinking concepts in the analysis of major incidents and safety culture	Reference modes and causal loop diagram	"… demonstrates the use of systems thinking and causal loop diagrams through a case study on Bellevue hazardous waste fire in Western Australia"	Qualitative; case specific analysis; single case

Out of the eight articles, four of the articles used only qualitative method and the other four used mainly stock and flow simulation. Three of the four articles that used stock and flow simulation also used causal loop diagrams to represent dynamic hypotheses (Sterman 2000). Even though Rudolph and Repenning (2002) did not use causal loop diagram to describe its hypothesis, the article explained its theoretical propositions textually prior to simulation. The four qualitative papers used a mix of reference modes (or behavior over time charts), causal loop diagrams and influence diagrams (or root cause analysis) for the analyses. As a whole, five of the eight papers model actual cases, while Rudolph and Repenning (2002), Cooke and Rohleder (2006), and Marais, Saleh and Leveson (2006) created their models based on existing literature.

Classification of Papers

Sterman (2000) emphasized the importance of grounding system dynamics model based on data, but when Kopainsky and Luna-Reyes (2008) conducted a review of 51 papers from the *System Dynamics Review* between 2003 and 2006, they found that most of the papers do not report their methods or data collection techniques. Similarly, as can be observed in Table 2, with the exception of Rudolph and Repenning (2002), the papers reviewed did not clearly explain their methods.

Table 2 Analysis of papers based on Kopainsky and Luna-Reyes (2008)

Author-Date	Methods reported?	Methods classification
(Tsuchiya et al. 2001)	No	A
(Rudolph and Repenning 2002)	Yes	B
(Cooke 2003)	No	A
(Cooke and Rohleder 2006)	No	B
(Marais, Saleh, and Leveson 2006)	No	B
(Salge and Milling 2006)	No	A
(Laugé, Sarriegi, and Torres 2009)	No	A
(Goh, Brown, and Spickett 2010)	No	A

A – Model-based papers that describe case studies B – Model-based papers that use general model(s)

As indicated in Table 2, the papers are essentially model-based papers that either describe organizational accidents (type A) using a system dynamics model, or use general model(s) (type B) for broad-based analysis or discussion of organizational accidents. Since organizational accidents are inherently case-based, it is not surprising that case study approaches (type A) are frequently used to study them. Incidentally, case study is identified by Kopainsky and Luna-Reyes (2008) as one of the key social research methods relevant to system dynamics model development. Within Table 2, Marais, Saleh, and Leveson (2006), Cooke and Rohleder (2006) and Rudolph and Repenning (2002) did not use a case study approach in their paper. Rudolph and Repenning (2002) and Cooke and Rohleder (2006) created their system dynamics model based on existing literature or theories and tested the model to confirm or extend the theory and model (type B). Their models were not directly applied on any organizational accident. Marais, Saleh, and Leveson (2006) qualitatively proposed a set of archetypes for organizational accidents, but did not test the archetypes. Type A papers are essentially “practice-to-theorizing” (Kopainsky and Luna-Reyes 2008) because they establish theories or lessons deductively, i.e. based on cases or actual data. Type

B papers can be classified as "theorizing-to-practice" (Kopainsky and Luna-Reyes 2008) because they start with a general theory and test the theory through simulation or case studies.

Practice-to-theorizing (Type A)

The traditional approach to the study of organizational accidents is to evaluate the accident and derive useful theory to aid prevention. Hence, five of the eight papers in Table 2 are type A, but as discussed earlier the papers did have clearly defined method and did not ground the models in data explicitly. The type A approach are similar to intrinsic case studies (Stake 2000), where an accident is studied because of the interest in the accident itself or its intrinsic value for learning. Due to the availability of written and mental data (Sterman 2000) created during the public inquiries and investigations into the organizational accidents (Hopkins 2006), the practice-to-theorizing approach is usually viable. The data collection would be focused on inquiry reports, investigation reports, proceeding transcripts, media reports and other evidence submitted during the accident inquiry. On the other hand, due to the large amount of (potentially conflicting) data generated during inquiry, it is pragmatic for researchers to focus on the final inquiry report initially and use the other data sources as supplementary. This research strategy is feasible if the researchers feel that the inquiry report is sufficiently comprehensive and representative of the accident.

To improve the robustness of type A papers, it is proposed that key relationships, equations or loops in the model should be supported by textual data from inquiry reports. To achieve this level of rigor, the coding approach adopted by Burchill and Fine (1997) can be adapted as follow:

1. Open coding[2] of data sources based on the fundamental research questions, "what factors or systemic structure contributed to the occurrence of the accident?"
2. Reflect on the open codes to identify topic(s) of interest, e.g. production pressure, risk management and safety culture, and conduct focused coding based on the topic(s) (axial coding or theoretical sampling).

[2] Coding is commonly used in social research to refer to the classification of data, usually textual, into useful themes or categories to facilitate construction of models. Nowadays coding is typically conducted using qualitative research software.

3. Evaluate the coded data using Boolean searches and identify possible linkages between the codes. For example a Boolean search with the "AND" operator for the variables, "production pressure" and "management emphasis on production", may reveal that the two codes overlap significantly. If this is the case the textual data with both codes should be inspected and if appropriate a relationship such as the following can be established:

$$production\ pressure\ \xrightarrow{+} management\ emphasis\ on\ production$$

4. After step 3, a model that depicts the relationship between the variables (codes) will emerge from the data. Challenge the emerging model constantly by: (a) considering rival theories of relationship between codes (or variables), (b) merging variables if there are similar constructs and (c) creating new variables based on new insights or data. Coded data will have to be re-coded if the coding scheme changes.
5. Continue coding iteratively until the model stabilizes with no further changes to the coding scheme and classification of textual data.
6. Evaluate the model holistically and modify the model using expansion analysis[3] (Gephart 1993) or additional sources of data, e.g. expert opinion.
7. Convert the qualitative model into a simulation model. Additional expert opinion and literature review may be necessary to assign the values for mathematical equations in the simulation model. (As long as the simulation model is tied closely to the qualitative model, the final simulation model will still be grounded in data.)

Theorizing-to-practice (Type B)

The three theorizing-to-practice (type B) papers in Table 2 studied organizational accidents in a more generic sense. As discussed earlier, Marais, Saleh and Leveson (2006) provided a set of organizational safety archetypes customized based on the literature, but the study did not subject the archetypes to testing and validation. Thus, the paper is not further analyzed. Cooke and Rohleder (2006) and Rudolph and Repenning (2002) are similar in their approaches. The former will be discussed herein. Cooke and Rohleder (2006) argued that an

[3] Expansion analysis is the conceptual interpretation of the hidden meanings and features of texts (Cicourel 1980)

incident learning system is critical in reducing the chance for organizational accident. The authors created the simulation model based on the literature and logical argument. Subsequently, the model was subjected to testing to assure the face validity of the model. A set of scenarios were then evaluated using the model to derive useful lessons for prevention of organizational accidents. Even though the study did not conduct detailed sensitivity analysis method, it is generally aligned with Sterman's (2000) guidelines.

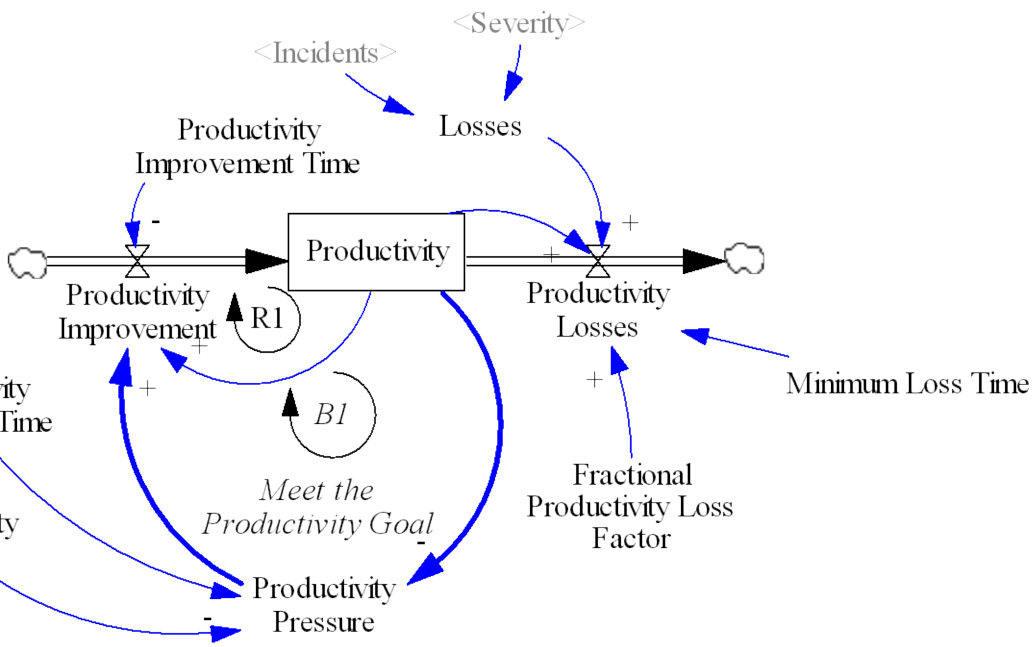

Figure 1 Productivity sub-system (adapted from Cooke and Rohleder 2006)

To ensure that the model is grounded in data one alternative is to ensure that the hypothetical model is tested either through instrumental case study (Stake 2000), organizational accident expert assessment or both. An instrumental case study uses a pre-conceived theory (the dynamic hypothesis) to conduct a case study (or multiple case studies) so as to challenge, extend or confirm the theory. Through this process, the validity of the theory is improved. Using Cooke and Rohleder (2006) for illustration, prior to scenario testing, the model can be used to create a coding scheme that can be applied on inquiry reports of organizational accidents to identify data that support or oppose the relationships in the model. To facilitate systematic coding, the codes can be hierarchical with sub-systems as the first level codes, loops as second level codes, relationships between variables as third level codes and variables (including parameter values) as fourth level codes. With reference to Figure 1, the data relevant to the productivity sub-system can be coded with "productivity sub-system”. Once the code “productivity sub-system” has been applied on the whole report (assuming there is only one data source), the coded data is then further categorized into loop B1 (“meet the productivity goal”), loop R1 and variables not in loops. Accordingly the data coded under each second level code (e.g. loop B1) is then further classified under the links within the loop, for example:

$$production\ pressure \xrightarrow{+} productivity\ improvement$$

Variables and relationships not supported by data may need to be further established based on literature and expert input. Even though the coding process should be as detailed as possible, it may not be practicable to fully validate a large model such as the one presented in Cooke and Rohleder (2006). Thus, it is advisable to create causal loop models to represent the key dynamic hypothesis which can then be validated via the coding process described earlier. Subsequently the qualitative model can be converted into a simulation model.

Conclusions

System dynamics tools are now being recognized as a valuable tool for the analysis and theorizing of organizational accidents. However, this study identified that the methods used in current studies can be strengthened. As a whole, there is a lack of grounding of the system dynamics models, both qualitative and simulation models, in textual data commonly available in inquiry reports and other relevant documents. Eight system dynamics papers on organizational accidents were identified in this study. Five of them described organizational accidents using system dynamics tools (practice-to-theorizing). These papers generally do not have very clearly described methods. An intrinsic case study approach was thus proposed to improve the robustness of such studies. Instead of focusing on specific organizational accidents, the other three papers reviewed started with a pre-conceived theory (theorizing-to-practice). Out of the three papers, two papers used simulation methods to test the model to derive useful insights on organizational accidents. To improve these studies, it is suggested that the initial dynamic hypothesis should be tested using an instrumental case study with hierarchical coding scheme based on the hypothesis.

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