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Research Article

INVESTIGATING LINEAR MODELS OF ACCIDENT CAUSATION: A REVIEW STUDY IN THE CONSTRUCTION SAFETY CONTEXT

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ABSTRACT

A major challenge of today is to prevent accidents from occurring in the construction industry. Hence, the causes of accidents need to be defined at the first step. Due to the emerging need for determining causes of accidents, several accident causation theories and models are developed. However, traditional accident modeling approaches are insufficient to analyze accidents occurring in complex environments. Accidents do not only occur due to human factors but also occur due to mechanical and environmental factors. Hence, a more systemic approach is crucial in accident modeling research. This paper reviews key traditional accident causation theories and models and lists their strengths and limitations. The main contribution of this paper is to reveal the lacking points of existing accident causation approaches, emphasize the need for more essential causation models, and encourage safety practitioners to develop more efficient accident prevention strategies. In this respect, the paper presents linear accident causation models, which are traditional theories of accident causation focusing on linear sequence of events. The paper is expected to guide health and safety practitioners to find the real causes of accidents by means of a systematic analysis and understand the process for accident analysis and prevention.
Keywords: Accident causation models, safety, safety management, construction.

1. INTRODUCTION

The construction industry is vulnerable to hazards and risks and there is a growing need for more efficient and reliable safety measures. According to Occupational Safety and Health Administration (OSHA) statistics, it was reported that 4,779 worker fatalities were recorded in the private industry in year 2018, whereas 1008 or 21.1% of them were in construction. The leading causes of fatalities in construction were reported as falls, struck by object, electrocution, and caught-in/between, which are also named as “fatal four”. The “fatal four” were responsible of 58.6% of all worker deaths in construction in 2018 [1].

The alarming rates of accidents requires the understanding of root causes of accidents in a systemic way to improve safety in the construction industry. Therefore, it is essential to specify conditions, actions, and events for accident analysis with the knowledge gained through the root cause of accidents [2]. To develop this understanding, accidents causation tools or models are of utmost importance [3]. However, accident causation models are often times criticized due to their practical value and generalizability in terms of explaining construction accidents [4]. On the other

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hand, it was emphasized that idenfication of differences in the patterns of accident causation might help for accounting for the fatal and major accidents [5].

It is possible to prevent construction accidents from occurring with a proper identification of root causes such as utilizing the theories of accidents causation or focusing on the human error leading to the accidents [6]. Among accident causation theories developed, there are both linear and nonlinear models of causation. In safety science, accidents causation is analyzed in terms of three distinct type of models, namely (i) the simple linear models, (ii) complex linear models, and (iii) complex nonlinear or systemic models. Simple linear models present an early thinking, where a series of predictable linear events c ould be prevented by eliminating one of more root causes in a linear sequence. The complex linear models came up with a significant shift from early thinking of accidents causation [3, 7, 8]. Complex linear models are rather focused on the interaction of underlying latent conditions and the unsafe human acts [9]. Finally, complex nonlinear or systemic models are more focused on system wide factors and complex associations between organizations, technology, behaviors, individuals, and factors [8]. These models rather indicate that the errors stem from the systemic problems than human related errors.

Given this background, this paper aims to investigate the most common accident causation theories or models focusing on management aspects, physical characteristics of hazards, and people. The paper aims to develop a deeper understanding of accident causation theories highlighting the benefits and limitations in terms of preventing accidents. In this respect, the paper underlines the critical role of accident causation theories to explain how hazards lead to losses at construction sites.

2. LINEAR MODELS OF ACCIDENT CAUSATION

As mentioned in the introduction section, accident causation models are classified as simple linear models, complex linear and complex nonlinear models. Simple linear models of accident causation rely on the fact that indicents happen due to a predictable and linear series of events, which might be prevented with the elimination of the one of the root causes in the chain of events [3, 7, 8]. These models mostly rely on failures caused by human error due to isolated physical or mechanical components. On the other hand, complex linear models assess incidents based on the interaction of underlying conditions and unsafe human acts [9].

As emphasized above, linear accident causation models rely on a sequence of linear events leading to an accident. Linear accident causation models are rather considered as older and traditional models for analyzing root causes of accidents. Among those, the most common theories and models are Domino theory developed by [10] Heinrich (1936), Swiss Cheese Model developed by Reason (1997) [11], and Rasmussen's socio technical framework (1997) [12]. This study first discusses these three linear models in addition to Normal Accidents Theory developed by Perrow (1984) [13] and STAMP (System-Theoretic Accident Model) approach developed by Leveson (2004) [14].

Linear models of accident causation are the ones that mostly explain the causations behind construction accidents. However, these models are criticized due to the taxonomy that they advocate. For example, Heinrich's domino theory is putting the focus on the human error claiming that majority of the accidents are caused by the unsafe acts of people. Even though this might be valid for some cases, it is hard to claim that accidents at construction sites mostly stem from the unsafe acts of people since the systemic errors are also the cause for some major accidents. Hence, one might state that accidents might be eliminated or prevented by improving the system rather than focusing on the unsafe acts of people. Similarly, normal accidents theory addresses a very small portion of incidents limiting its use and capability to provide causation for accidents. Considering the dynamic nature of construction projects, it is somewhat difficult to portray a clear map for investigating causations behind accidents. However, the systemic models help developing an understanding of how accidents might be analyzed from a scientific perspective and tackle measures to avoid accidents with causation techniques. Therefore, this study presents the accident causation theories and models dominating the construction safety research along with providing their main benefits and limitations.

2.1. Domino theory

Heinrich [10] in 1936, a safety pioneer, developed his Domino theory. Domino theory implies that 88% of all accidents are caused by unsafe acts of people, 10% by unsafe actions and 2% by "acts of God." Hence, a five-factor accident sequence was proposed by [10] in which each factor would actuate the next step in the manner of toppling dominoes lined up in a row. The sequence of accident factors is shown in Figure 1. This figure graphically illustrates the sequentiality of events Heinrich believed to exist prior to and after the occurrence of accidents. Heinrich had five dominoes in his model: ancestry and social environment, fault of person, unsafe act and/or mechanical or physical hazard, accidents, and injury. This five-domino model suggested that through inherited or acquired undesirable traits, people may commit unsafe acts or cause the existence of mechanical or physical hazards, which in turn cause injurious accidents. Heinrich defined an accident as follows: ''An accident is an unplanned and uncontrolled event in which the action or reaction of an object, substance, person, or radiation results in personal injury or the probability thereof.'' The work of Heinrich can be summarized in two points: people are the fundamental reason behind accidents; and management—having the ability—is responsible for the prevention of accidents [15]. This theory is investigated as part of the simple linear models.

Some of Heinrich's views were criticized for oversimplifying the control of human behavior in causing accidents and for some statistics he gave on the contribution of unsafe acts versus unsafe conditions [16]. Nevertheless, his work was the foundation for many others. Over the years the domino theory has been updated with an emphasis on management as a primary cause in accidents, and the resulting models were labeled as management models or updated domino models.

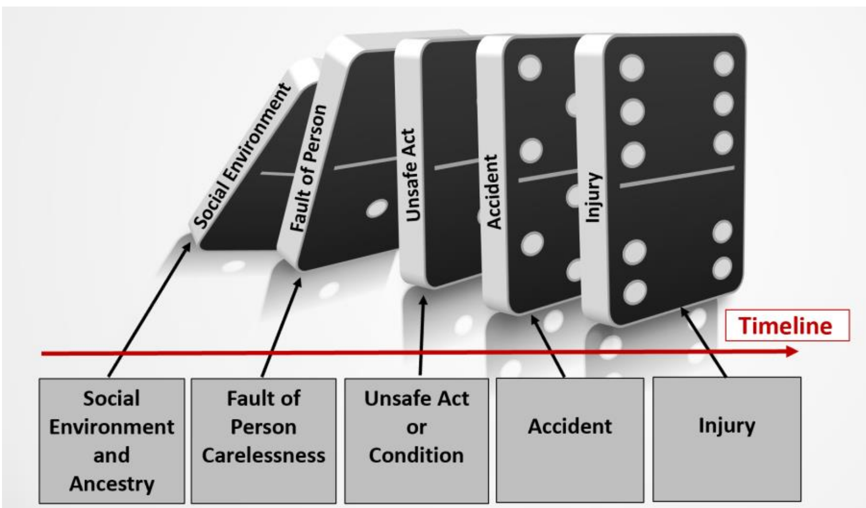

Figure 1. The Domino Theory (Adapted from [10])

2.2. Swiss Cheese Model

Swiss Cheese model was developed by Reason [11] in 1997. In place of Heinrich's domino model of accident causation, the dominant image here in the deterministic systems-centered investigations has been Reason's "Swiss Cheese Model". In the Swiss Cheese model, Reason conceptualizes a system as having a series of defense layers to detect and prevent error, but each of those layers is imperfect, i.e., they have holes in them (termed as active and latent failures). The necessary condition for an organizational accident is the rare conjunction of a set of these holes in successive defenses, allowing hazards to come into damaging contact with people and assets. This model has flourished for decades and is responsible for many of the lessons now generally adopted. Numerous organizational factors were identified as the causal factors that contributed to the probability of the accident. This model is presented as part of the complex linear models. However, this model does not give a clear explanation how these causal factors combined to provide the circumstances for an accident to take place [17].

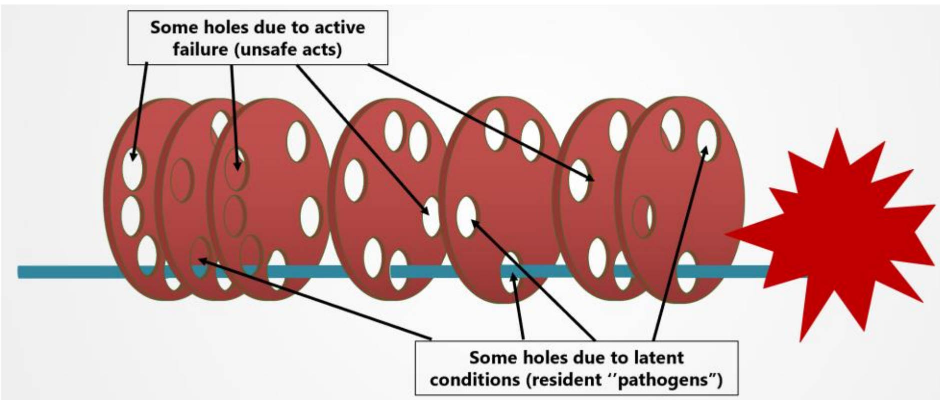

Figure 2. Swiss Cheese Model (Adapted from [11])

2.3. Rasmussen's socio-technical framework

The complexity and rapid advancements in technology have led to the development of high-risk socio-technical systems, which are managed by complex organisations operating in highly volatile and dynamic environmental conditions such as market competition, economic and political pressures, legislation and increasing social awareness on safety [12]. Rasmussen postulates that these factors have transformed the dynamic character of modern society and continuously influence the work practices and human behaviour in the operation of complex systems. Deterministic (e.g. sequential chain-of-events) causal models are inadequate to study failures and accidents in highly adaptable sociotechnical systems. Rasmussen adopts a system-oriented approach based on control theoretic concepts and proposes a framework for modelling the organisational, management and operational structures that create the preconditions for accidents. This system is assessed as a complex linear system. Rasmussen's framework for risk management has two parts: Structure and Dynamics.

2.3.1. Structural Hierarchy of Rasmussen's framework

Rasmussen [12] in 1997 views risk management as a control problem in the socio-technical system, where human injuries, environmental pollution, and financial disasters occur due to loss of control of physical processes. According to Rasmussen, safety depends on the control of work processes in the context of the pressures and constraints in the operational environment. The socio-technical system involved in risk management includes several hierarchical levels ranging from legislators, organisation and operation management, to system operators (Figure 3).

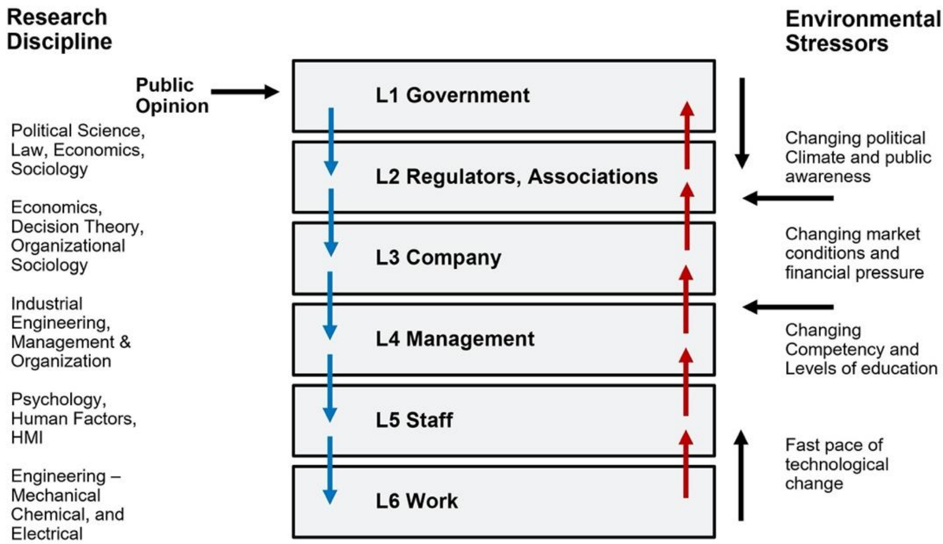

Figure 3. Hierarchical system of socio-technical framework

2.3.2. System Dynamics of Rasmussen's framework

Decision making and human activities are required to remain between the bounds of the workspace defined by administrative, functional and safety constraints. Rasmussen argues that in order to analyse a work domain's safety, it is important to identify the boundaries of safe operations and the dynamic forces that may cause. The socio-technical system to migrate towards or cross these boundaries. Figure 4 shows the dynamic forces that can influence a complex socio-technical system to modify its behaviour over time. The safe space of performance within which actors can navigate freely is contained within three boundaries: individual unacceptable workload; financial and economic constraints; and the safety regulations and procedures. The financial pressures produce a cost gradient that influences individual human behaviour to adopt more economically effective work strategies; while workload pressures result in an effort gradient motivating individual to change their work practices to reduce cognitive or physical work. These gradients induce variations in human behaviour that are analogous to the "Brownian movements" of the molecule of a gas [18].

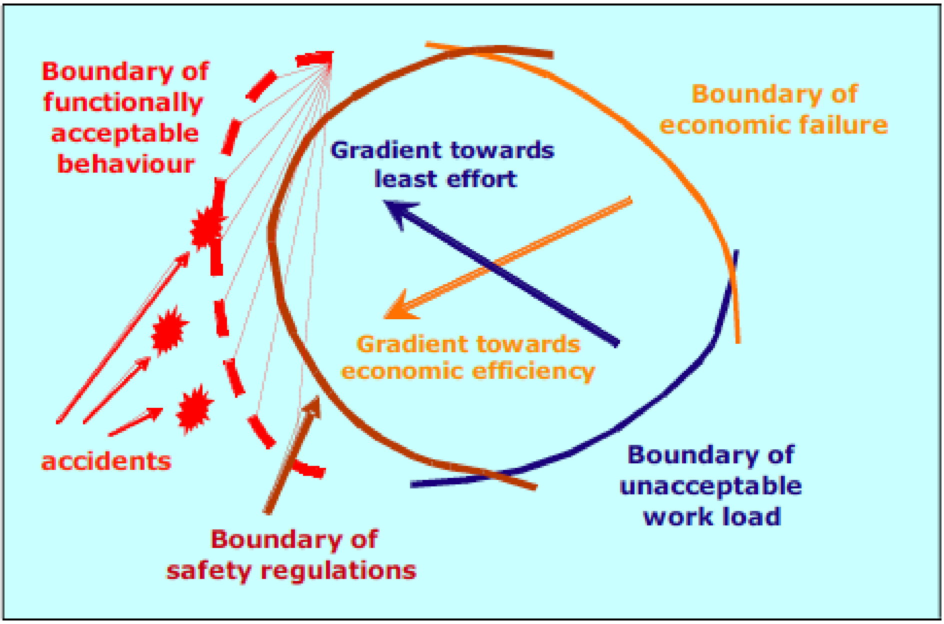

Figure 4. Boundaries of Safe Operation [12]

Over a period of time, this adaptive behaviour causes people to cross the boundary of safe work regulations and leads to a systematic migration toward the boundary of functionally acceptable behaviour. This may lead to an accident if control is lost at the boundary. Rasmussen asserts that these uncoordinated attempts of adapting to environmental stressors are slowly but surely "preparing the stage for an accident". Reports from several accidents such as Bhopal and Chernobyl demonstrate that they have not been caused by coincidence of independent failures and human errors, but by a systematic migration of organisational behaviour towards an accident under the influence of pressure toward cost-effectiveness in an aggressive, competitive environment [12]. Rasmussen's approach for improving safety and risk management raises the need for the identification of the boundaries of safe operation, making these boundaries visible to the actors and giving opportunities to control behavior at the boundaries.

2.4. STAMP Approach

Leveson (2004) [14] proposes a model of accident causation that considers the technical (including hardware and software), human and organisational factors in complex socio-technical systems. According to [14], "The hypothesis underlying the new model, called STAMP (Systems-Theoretic Accident Model and Processes) is particularly system accidents." In the STAMP approach, accidents in complex systems do not simply occur due to independent component failures; rather they occur when external disturbances or dysfunctional interactions among system components are not adequately handled by the control system. Accidents therefore are not caused by a series of events but from inappropriate or inadequate control or enforcement of safety-related constraints on the development, design, and operation of the system. "Safety then can be viewed as a control problem, and safety is managed by a control structure embedded in an adaptive socio-technical system" [14]. A STAMP accident analysis can be conducted in two stages: 1) Development of the Hierarchical Control Structure, which includes identification of the interactions between the system components and identification of the safety requirements and constraints; 2) Classification and Analysis of Flawed control (Constraint Failures), which includes the classification of causal factors followed by the reasons for flawed control and dysfunctional interactions [19, 20].

2.5. Normal Accidents Theory

Normal accident theory was proposed by [13]. His theory targets the intersection between complex technological systems and human management practices. Some specific targets of his analysis are high-risk enterprises using high-risk technologies, such as nuclear power plants, petrochemical plants, supertankers, major airport systems, hydroelectric dams and the like – systems with high catastrophic potential. However, in discussing what differentiates these systems from less risky systems, he creates a general typology of systems. This typology names dimensions that lie near the core of the structure of concern [21].

3. DISCUSSION OF ACCIDENTS CAUSATION MODELS

This study presented five most commonly recognized linear models of accident causation. However, these traditional methods are often times favored or criticized depending on their benefits of limitations. Therefore, it is essential to scrutinize and discuss the scope, benefits, and limitations provided by each linear model. Table 1 presents these along with the relevant references.

Table 1. Scope, Benefits, and Limitations of Linear Accident Causation Models

	Scope	**Benefits**	**Limitations**	**References**
Domino Theory	Event based accident causation model, static, deterministic.	Works well for losses caused by failures of physical components or human errors in relatively simple systems.	Cannot comprehensively explain accident causation in modern socio-technical systems.	[22, 23]
Swiss Cheese Model	Linear combination of active failures and latent conditions (to several event chains). Accidents are seen as occurring due to several events that coincide static.	Looks for the accident beyond the proximate causes, which is advantageous in the analysis of complex systems that may present multiple causality situations. Numerous organizational factors were identified as causal factors that contributed to the probability of the accident	Difficult to describe and understand how multiple factors can come in line simultaneously to produce something as disastrous as a blowout. Inadequate to capture the dynamics and nonlinear interactions between system components in complex socio-technical systems.	[24-26]

Socio-technical Framework	Safety as an emergent property impacted by decisions of all actors, at all levels, not just frontline workers alone. Dynamic work practices.	Attempt to model the dynamics of complex socio-technical systems.	Raises the need for the identifications of boundaries of safe operation, making these boundaries visible to the actors and giving opportunities to control behavior at the boundaries.	[18, 27]
STAMP	Integrates engineering analysis into causal factors such as software, human decision-making and human factors, new technology, social and organizational design, and safety culture	It provides a comprehensive approach and a taxonomy of controlling failures allowing a multi case analysis. It is a simple tool, which does not require a special analytical skill or expertise. It defines violations against existing safety constraints along with the causes of their failures.	It does not take reliability and probability into account. It is way behind a quantitative approach and it is a complex system involving. several variables and controllers requiring the definition of system limits.	[28, 29]
Normal Accidents Theory	Accidents are considered as normal for complex systems.	It provides traceability. It enables the prediction of interaction complexity and coupling.	It applies to a very small incident category. Its concepts are poorly defined leading to serious problems for detecting the scope of the theory. Basic insights from organizational sociology are missing. It identifies accidents as inevitable due to complex systems.	[30-32]

As summarized on Table 1, the investigated theories or models of accident causation have various benefits and limitations. These benefits and limitations might be attributed to certain cases in the construction industry context. For example, as a dominant example of simple linear models, Heinrich's domino theory fails to explain complex sequence of events leading to accident. However, construction accidents are mostly complex in nature and they cannot not be attributed to human error only. Therefore, simple linear models often times fail to provide causation for construction accidents. Regarding the complex linear models, one might advocate that construction accidents might be better explained with the complex linear accident causation models since they consider the occurrence of an event on a series of complex chain of events. On the other hand, complex linear models fail to address the dynamic and nonlinear interactions between system components. Considering the dynamic and project-based nature of construction projects, complex linear models might also fail to develop causations construction incidents. The use of socio-technical frameworks might best fit the nature of construction incidents since they direct to make the boundaries visible to actors emphasizing a transparent of process operation. Therefore, complex socio-technical frameworks might be effectively implemented to explain the causes of construction incidents. STAMP approach rather integrates engineering analysis into causal factors, which might help avoiding incidents thanks to the taxonomy of controlling failures. However, it lacks taking into account reliability and probability, where construction accidents are often times assessed with the consideration of those. Finally, normal accidents theory is presented with various benefits it provides on the prediction of interaction complexity. On the other hand, this theory is applied to a very limited incident category, preventing it from being generalizable for all incident categories. Therefore, the theory lacks providing causation for a wide array of construction incidents.

4. CONCLUSIONS

Accident analysis and prevention is essential in terms of enhancing safety performance in the construction industry. To achieve this, the industry is developing ways towards enhancing their safety performance. One of the milestones in accident prevetion is to identify the root causes. The root causes might be defined with a wide variety of methods such as root cause analysis, accident causation techniques, and models of accident causation. This study aimed to discuss the linear models of accident causes theories and models, which have been commonly used in various studies for analyzing accidents. In this respect, five accident causation theories and models- Domino theory, Swiss Cheese Model, Rasmussen's socio technical framework, STAMP approach, and Normal Accident Theory- were discussed. The scope, benefits, and limitations of these methods are provided along with the justification from previous studies. The investigation of the existing theories and models of causation indicated that each of these theories or models have various flaws or strengths in practice. These theories and models provided that they mostly lack from explaining consequences caused by the nonlinear events, which represent the nonlinear interaction of sequential failure of accident contributory factors and where causal effects are nonlinear (i.e. competitiveness pressure affecting operators' and managers' performance as an indirect contributor). One major limitation of this study is that it only focused on linear models, whereas there are various nonlinear models of accident causation in the literature. On the other hand, linear models involve mostly cited theories and models of accident causation leading to an increasing popularity of conducting research in investigating those. Therefore, on might advocate that a complete analysis of these systems is a must to provide their impact in accident analysis and prevention. As a future work, researchers are encouraged to develop accident causation models or theories relating to a specific accident category (i.e. falls, electrocutions, struck-by-object) and compare the performance of these models or theories in terms of reducing the number of accidents. Conducting a similar study with nonlinear models is also proposed as a future work. Moreover, the models provided in this study might guide industry practitioners in terms of conducting a comprehensive root cause analysis for accidents occurring at their workplaces.

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