# A Review of Functional Safety Models for Public Safety Management Systems

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This paper reviews various models used for enterprise process management systems and public safety systems. These models include probabilistic functional safety models, accident models such as causal-sequential event-based models, systemic models such as failure mode and effects analysis (FMEA), reliability models, systemic models such as systems-theoretic accident model and processes (STAMP) model and cognitive models, among others. These models, along with their advantages and disadvantages, are discussed in detail. Existing public safety management systems and enterprise process management systems are also compared. Functionally safe communication systems for public safety, including those using wireless telecommunications such as *LTE for Public Safety*, are also discussed. In addition, this paper also explains some of the evolving legislation regarding managed energy and managed safety for both process and public management systems.

## Introduction

Safety management systems (SMS) are part of the management controls that operate an organization. SMS strives to provide adequate safety during failures that occur in routine operational procedures. These failures can be systemic or systematic, and may be caused by human and non-human factors. SMS has various stages, including detection of failure, prediction of failure and prevention and control of failures that have the potential to create tangible and intangible loss to the organization.

Enhancing overall safety in the most efficient manner requires the adoption of a systems approach to safety management. Every level of an organization must become part of a safety culture that promotes and practices risk reduction. Safety management is based on the premise that there will always be safety hazards and human errors. SMS establishes processes to improve communication about these risks and to take action to minimize them. This approach will subsequently improve an organization's overall level of safety.

There are multiple safety regulations governing occupational safety, such as Occupational Safety and Health Administration (OSHA) regulations. Asset safety is governed by equipment safety regulations, as well as functional safety and safety management systems guidelines provided by respective industries and as per the International Organization for Standardization (ISO) requirements for quality management (ISO 9001) and environmental management (ISO 14001). Life and fire safety codes created by organizations like the National Fire Protection Association (NFPA) mandate compliance with the fire and life safety regulations in built environments. The upgrading of public safety communications must consider such compliance. The availability of regulations helps us get to know the operational boundaries of systems. It is also understood that regulations merely provide an operational framework; different industries and systems update them as per their respective requirements.

In a public safety system monitoring a particular space, it is imperative that different safety management systems collaborate to protect citizens. In adopting a systems approach to safety management, the role of modeling in safety management and accident prevention becomes clear. Different models for accident causes and prevention have been developed — e.g. FMEA, FTA, STAMP, FRAM, Swiss Cheese, Domino Model, etc. — to give an overview of failure modes and their prevention, as well as the nature of human roles in accidents.

This work is part of ongoing research in safety communication systems design using public safety broadband LTE networks. Public safety broadband LTE networks are specific broadband networks for public safety use alone. They are designed to replace terrestrial trunked radio (TETRA) and land mobile radio (LMR) services, which cannot communicate large amounts of data, as compared to the core architecture of LTE networks. Increased bandwidth will help emergency responders and regulators with both situational awareness and informed decision making. The existing safety management procedures analyzed in this paper and the existing research on accident models demonstrate the need for cognitive modeling of safety systems.

## Methodology

The scope of the project was to design a standardized public safety communication system that yields a usable backbone for safety management systems. As part of the nationwide implementation of broadband, extensive research has been undertaken to upgrade public safety communication network systems with LTE networking in the 700 MHz spectrum. Hence, this research used the LTE network as the main communication channel. To determine the suitability of using an LTE network, the needs of this communication system had to be identified. A review of available literature indicated that the suitability of networks is studied in emergency management scenarios alone. Use cases have been built around simply tackling an emergency situation, such as a fire, a chemical explosion or a medical emergency including ambulatory transport. These use cases are sufficiently drafted to handle emergency scenarios. Sufficient research and experiments on the suitability of LTE networks has also been performed. Yet the role of public safety management systems in other aspects of effective safety management has not been considered. Therefore, this research focuses on application models required by other safety management scenarios, and a hypothesis was created — i.e., that public safety systems could be built on similar platforms as safety management systems currently used in industry.

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Enterprise/industrial safety systems are designed in a functionally safe architecture, which includes the overall system design and continuous monitoring. They are typically a combination of systems, such as alarm management systems, safety sensing systems (gas controllers or fire alarm controllers), emergency shut-down systems, personnel protection systems, work procedure management, etc. Alarm management systems help with visualizing, archiving and creating situational awareness of process alarms, as well as safety alarms. These systems also help in incident investigation and post-incident analyses. Fire and gas safety controllers and detectors act as a layer of protection. Work management systems, including hot work permits and "lock-out tag-out" allow human operational controls. Personal protection systems and equipment provide a layer of individual protection and hazard prevention. The continuous monitoring and design of public safety systems occurs in conjunction with process safety systems. The California Public Safety Commission [Ref. 1], recently decided that the most approachable and implementable solution would be a "systems of systems" approach, rather than a single national broadband system.

Based on these theories of system safety, existing accident models were analyzed to control systemic faults. These faults are random in nature and are controlled through fail-over/fail-safe mechanisms. The control of systematic faults is a function of design and continuous monitoring. The communication system design will cater to the needs of both systemic and systematic fault avoidance at an overall system level. The existing functional safety models have established that the overall safety integrity is a function of the levels of integrity of each of the participating subsystems. For a sustainable safety management system, other aspects must also be considered — e.g., *planning*, *preparedness* and *periodic monitoring*. Human participation must also be considered in the process. The authors studied existing theories on *socio-technical* systems to better understand the human factors impact on this design.

## Public Safety System

Public safety includes the administrative actions and management of safety by providing near-immediate response to emergencies and disasters. The safety system also controls such scenarios through emergency medical response, firefighters, jurisdictional police agencies, criminal justice systems, operators of mission-critical 9-1-1 services and the regulatory authority to monitor the environment and pollution. The common need of any public safety department is to save lives and property in a sustainable manner. Every government has a department of public safety that is concerned with the identification, prevention and control of safety hazard incidents. This department is also often entrusted with


*Figure 1 — Process Safety Model Used in Industries.*

monitoring the environment and controlling pollution. As civic societies also include industries and associated workforces, this department must provide adequate safety measures to the industry and its workers, as well as the society in which the industry thrives. However, there are a number of instances in which such public safety systems have failed, as found in the examples of the Bhopal gas tragedy in India, the Gulf of Mexico oil spill in the U.S. and the recent ammonium nitrate fertilizer explosion in the city of West, Texas. These incidents show the need for better and more closely monitored safety management systems within the system of systems approach.

Incidents of safety failures and their hazardous impacts often result from inadequate knowledge of regulations, as well as poor implementation of regulatory requirements and training. In a recent report to the U.S. Senate regarding the explosions in the city of West, Texas, as well as another explosion in Louisiana, Dr. Sam Mannan noted, "Overall, from what is known, the storage of ammonium nitrate at West Fertilizer Company did not provide adequate measures to prevent overheating and propagation of fire, which eventually led to the explosion." He added that the status of the compliance with OSHA and DHS regulations was not clear and, if compliance had been met, such incidents could have been prevented [Ref. 2]. He also added that proper training on the hazards of ammonium nitrate and knowledge of a potential violent decomposition might have allowed firefighters to take a different approach when responding to and fighting the initial fire. It is evident from both older and newer cases that a

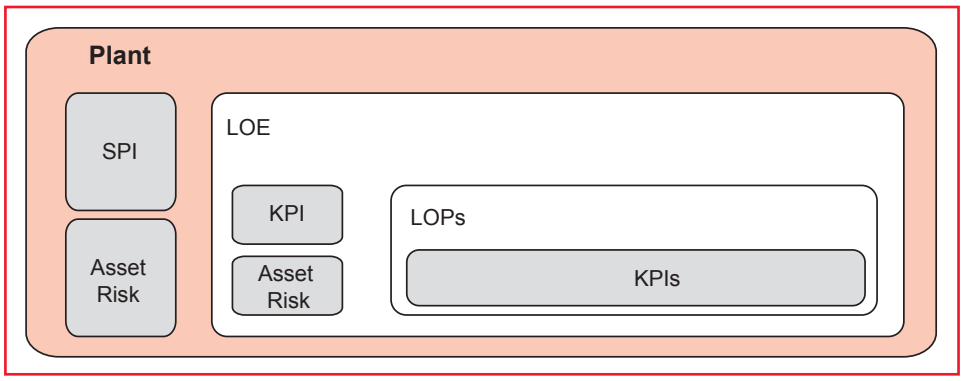


*Figure 2 — Safety Performance Index for a Plant.*

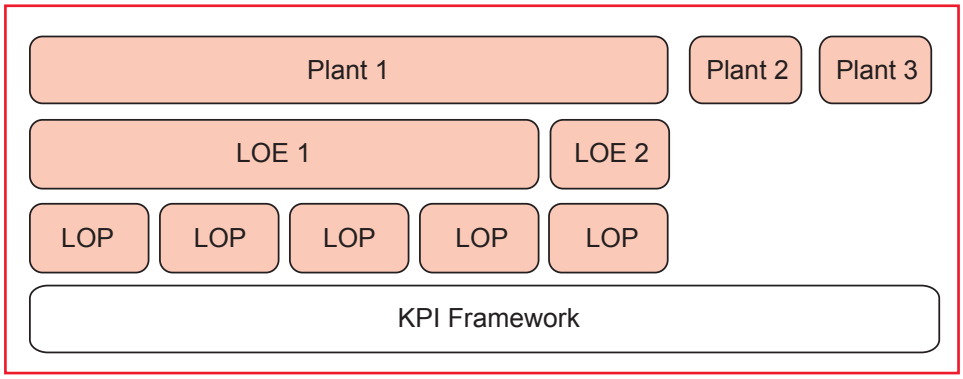


*Figure 3 — Key Performance Indicators for a Production Line.*

priori information and continuous compliance management would eventually help prevent such disasters. These cases further confirmed the need for executing disaster management using the principles of plant safety management and enabling compliance.

## Enterprise Process Safety System

Process Safety Management (PSM) systems are dedicated to controlling the process in industrial plants to prevent, predict and control disastrous incidents. Process safety management has evolved over the years in multiple dimensions, due to a strong focus on the business needs and economic value created from running processes safely. PSM will also lead to fewer downtimes and will help minimize expenses and losses from catastrophic accidents. PSM has used computer-aided safety engineering methodologies for more than a decade, and many PSM systems work under the premise of systemic safety integrity governed by probabilistic functional safety models. Figure 1 illustrates the PSM model.

In the above model, these elements of safety management act as a solution similar to control engineering problems. There are seven macro steps in the organizational process: planning, design and operation, audit, risk identification and management, training and practice, emergency preparedness and response, and management operating reviews. These steps play a critical role in industrial process control engineering, from planning to successful operation. The outputs of these steps produce a well-documented procedural methodology. But the real test and measure of this methodology is found in its economic value.

Safety management acts as a process lever by using safety management techniques to take control of operations management. These techniques must also comply with IEC-ISO standards for risk management, quality management, environmental protection and local labor laws, such as OSHA standards.

Even though some enterprises have developed their own internal safety management processes, they face challenges such as:

- Compliance
- Presumptions
- Tracking and measurement
- Business impact
- Systematic fault avoidance (which impacts the overall safety performance)

In a recent paper in Hydrocarbon Processing, Turk and Mishra [Ref. 3] explain the role of process safety management beyond functional safety principles by identifying the key performance indicators (KPI) and safety performance index, constructing a four-stage model as illustrated in Figures 2 and 3. Here, the KPI framework refers to the KPI, the layer of protection (LOP) and line of equipment (LOE). The authors list the following nine steps for effective industrial management that go beyond functional safety in an organization as a way to monitor and control risk and safety in the industry:

- Establish organizational arrangements/relationships needed to implement indicators
- Decide on the scope of the indicators
- Identify the risk-control systems and decide on the outcomes
- Identify critical elements of each risk-control system

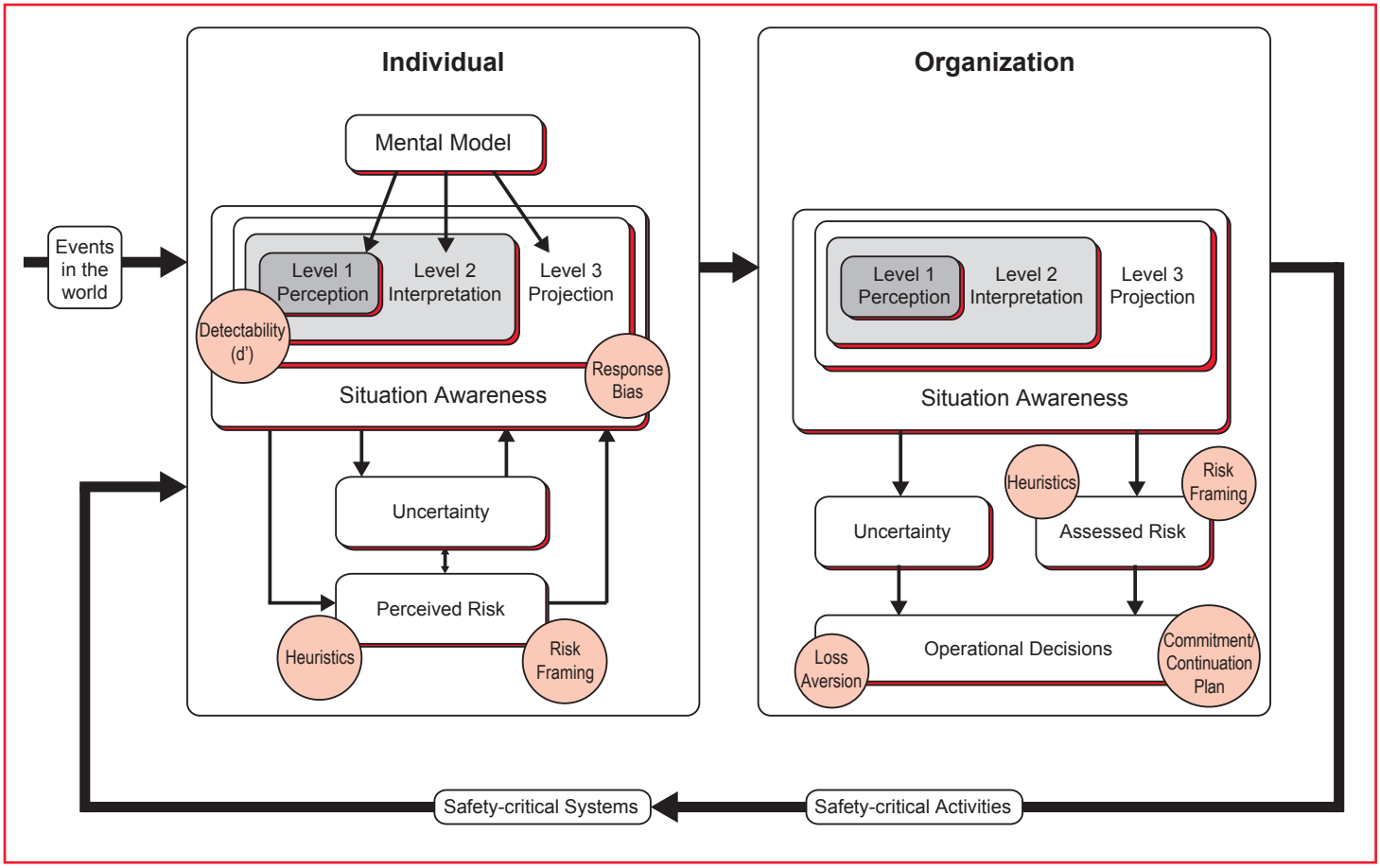


*Figure 4 — Cognitive Model in Process Safety Systems.*

- Establish a data collection and reporting system
- Review benchmarks against the IE PSM framework or its equivalent
- Deploy the KPI model and SPI calculations
- Educate management on the importance of PSM
- Establish management roles and necessary actions for review of KPIs, SPIs, estimated asset values at risk, and estimated production value at risk

The Abnormal Situation Management (ASM) Consortium has focused its research on plant safety from situation management and human factors perspectives. The Consortium's research has led to the identification of human factor effects and their cognitive implications [Ref. 4]. The International Association of Oil & Gas Suppliers has rolled out models of the role cognitive assessments may play in plant and environmental safety. The industrial safety management model includes foundation principles of functional safety management, with added layers of protection. Research has further detailed the functional safety models available and their applications, as well as the cognitive aspects of socio-technical systems.

## Models

Existing safety models were studied to understand the causes of accidents and these models were used in both investigation and prevention. Some of these models form the basis of the IEC/ISO regulations on functional safety. Additional ongoing research on system safety was also studied to understand causation behaviors and the impact of humans in the process loop. The following summary looks at the relevance of different models in the context of public safety management systems.

### IEC Functional Safety Model

The International Electrotechnical Commission (IEC) has developed the core framework for functional safety, i.e. IEC 61508. This framework considers functional safety as a lifecycle in the design, commissioning and operational phases of a product or a system. The model is extensively based on the probability theory of failure and the reliability of components, and goes on to develop hazard analysis — based on the perceived or potential risk — through techniques such as *Failure Mode Effect Analysis (FMEA)* and to develop component-level analysis using *Fault Tree Analysis* [Ref. 5]. The framework extends to safety integrity through continu-

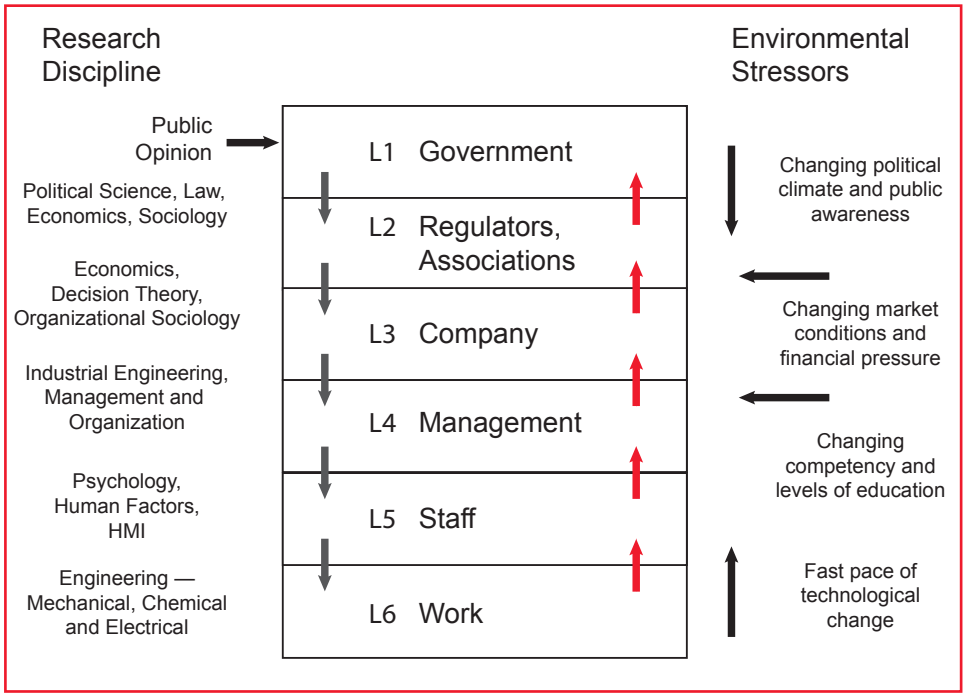


*Figure 5 — Implications of Human Factors in Safety Systems.*

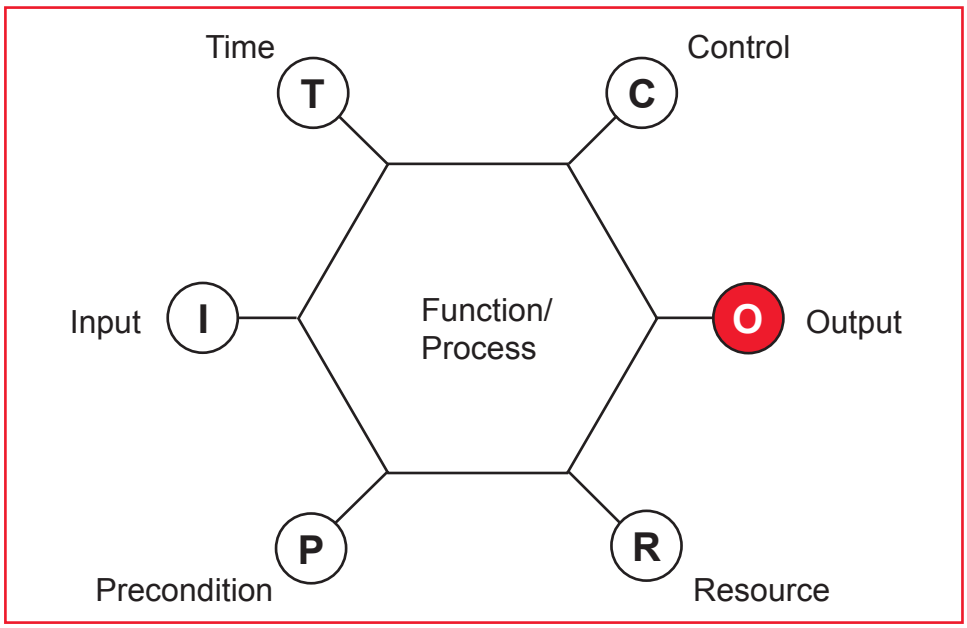


*Figure 6 — Framework for Process Safety Models.*

ous monitoring with fault diagnosis and proof tests for systems and subsystems. The 61508 model has itself manifested into specific applications for nuclear (IEC 61513), medical (IEC 62304), automotive (ISO 26262), process safety (IEC 61511) and rail (IEC 62279) classes. The latest development is the foundation classes for smart grids [Ref. 6]. Over time, system designers have resorted to functionally safe designs by increasing the perceived reliability through redundant architectures to fail safely, take over operations and continue operations.

The 61508 framework is reliably the best known technique to date to develop safety culture in electrical and electronic programmable systems. A public safety and emergency management system has lots of human interactions in the loop. For mostly automated systems, it is good to comply with the 61508 framework with additional knowledge of accident behaviors and associated human factors in accidents.

## Cognitive Model

Systems are a mixture of complex components, including humans. Most systems are built to meet human needs. Moreover, human interactions typically remain part of a system's use. Therefore, accidents are typically the result of mishandling or of dysfunctional interactions among components, rather than of component failures. Safety can then be viewed as a control problem, managed by a control structure embedded in an adaptive socio-technical system [Ref. 6].

The evolution of the safety of systems started with classic failure analysis aimed toward risk mitigation, with a further drive toward continuous improvements and safety controls as a business function. Since all systems and processes are designed for human use, continuous interactions with humans in social and technical systems are expected. The challenge in systems design is to integrate the other systems within a system-of-systems approach. The process of wider system integration includes human interaction, such as intuition of the user and his or her cognitive ability, fundamental underlying process knowledge and the impact of information and communication between the systems and users. Human cognitive abilities have always been linked to the safety of a system, as well as the safety culture in a society, whether in a workplace or a living space. Development of modern techniques has evolved the way humans work with these newly designed systems, and new failure modes have evolved in the way humans and machines interact. People working in the area of

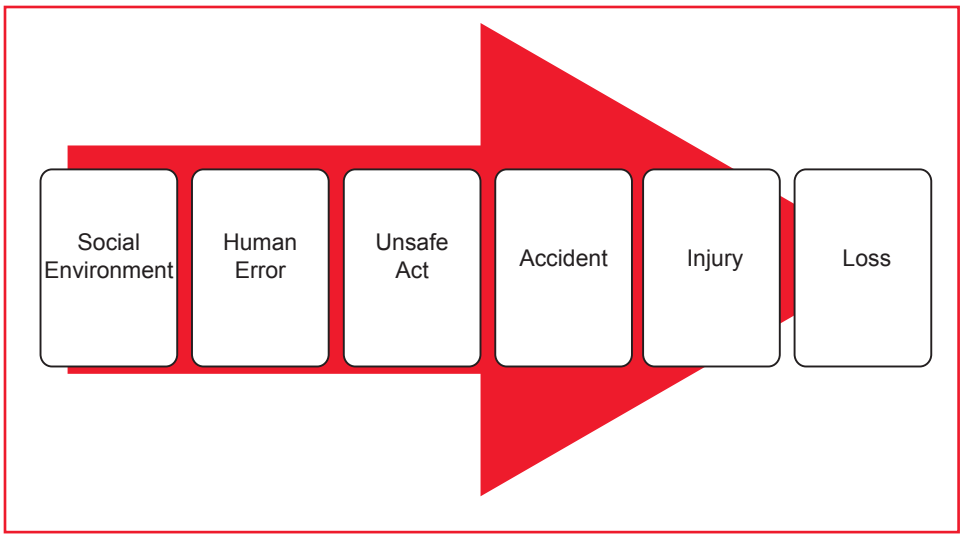


*Figure 7 — Causal Accident Model.*

cognitive systems engineering have developed models to validate this premise, which include Cognitive Reliability and Error Analysis Methods (CREAM). Erik Hollagnel is the developer of this technique, and he has applied it to two variants: road safety and maritime safety.

Functional Resonance Accident Models (FRAM) is yet another technique developed by Hollagnel to identify interactions between procedures, methods, systems and techniques in which functional entities or processes are analyzed.

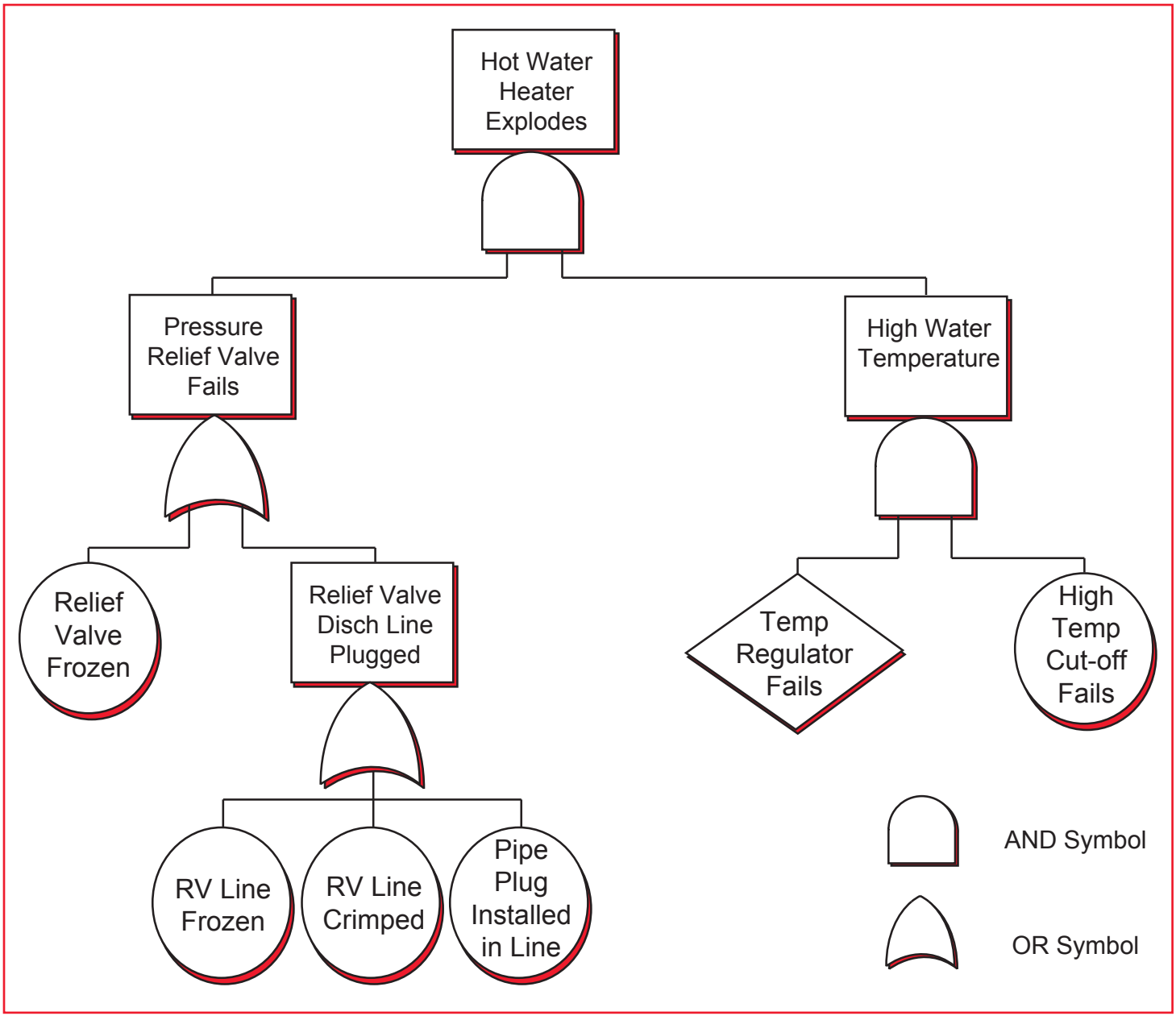


*Figure 8 — Systematic Hazard Analysis Techniques.*

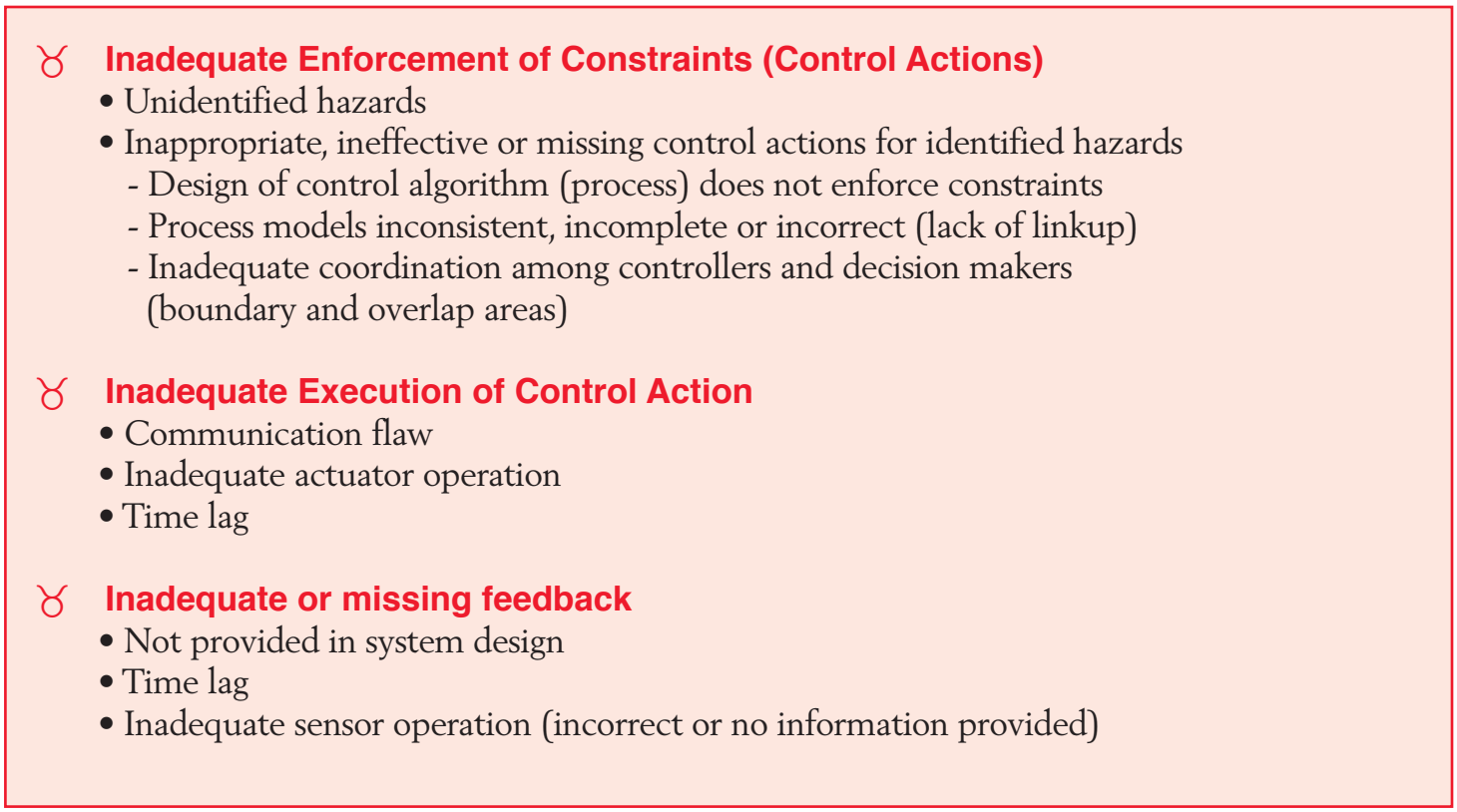


*Figure 9 — STAMP and Theory of Constraints.*

The parameters used are *input, pre-conditions, control, time* and *resource*. *The "time" parameter could be a time slot in the execution cycle or an event index order in the execution timeframe*. Thus, when analyzing the interactions between the various functions and processes, the interactions between the functions lead to a common mode and resonate to cause failures. This is an excellent model that dissects the system by systemic functions to develop predictable and controllable models of the system, rather than of the system structure. *System structures produce fault models at component levels, while the FRAM model helps predict and control processes and methods* [Ref. 7].

## Accident Models [Ref. 10]

### Causal-Sequential Event-Based Models

Heinrich's Domino Model of Accident Causation, mostly containing a single element as a root cause for a subsequent chain of events, is one of the oldest and most widely used models. This model, illustrated in Figure 7, performs well in uni-causal systems, i.e., subsystem-level analysis. This is due to the more or less linear trajectory of path between the cause and effect. However, Zahid Querishi of the Defense Systems Institute at the University of South Australia and Nancy Levenson of the Department of System Safety at the Massachusetts Institute of Technology found that this model is quite unsatisfactory, as most system failures are attributed to multiple sources. Therefore, the applicability of this model is limited.

### Systematic models like FMEA, reliability models, etc. [Ref. 9]

A systematic way of looking at safety has been a higher functional need and has contributed to the success of probabilistic models of system components failures and their reliability analysis. The most commonly known technique is the Fault Tree Analysis (FTA), which uses fault trees to identify or describe the state of the system, as illustrated in Figure 8.

### Systemic models

In systemic models, an accident occurs when several causal factors (such as human, technical or environmental) exist coincidentally in a specific time and space. A system is not regarded as a static design, but as a dynamic process that is continually adapting to achieve its objectives and react to changes in itself and its environment. The system design should enforce constraints on its behavior for safe operation, and must adapt to dynamic changes to maintain safety. Accidents are treated as the result of flawed processes involving interactions among people, social and organizational structures, engineering activities, and physical

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<tr><td>ISO 9001<br>Quality<br>Management</td><td>ISO 14001<br>Environmental<br>Management</td><td>AS/NZS 4801<br>OH&S<br>Management</td><td>NZS 7901<br>SMS for Public<br>Safety</td></tr>
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*Figure 10 — Public Safety model Used in the New Zealand 7901 Model.*

and software system components [Ref. 6]. Leveson has proposed a stronger model, Systems-Theoretic Accident Model and Processes (STAMP), which has its roots in Ramassuen's Socio-Technical Framework for complex systems.

### STAMP model

STAMP attributes systems failures to an inability to meet certain conditions that Leveson describes as systemic constraints or lack thereof [Ref. 8]. The other element applied in the STAMP model is flaws in the control loops between the systems during various phases from its design to deployment.

## Analysis

The comparison of enterprise/process safety management systems with public safety management systems helped the authors understand the subject of modeling public safety systems and its communication backbone. Enterprise safety management systems, with both publicly standardized safety management procedures and internal control procedures, continue to face the challenges mentioned earlier in this paper.

Even when the same model is applied to public safety systems, the challenges remain and are amplified because the scale of the system increases from an enterprise to a larger geography, with more people and more interactions. In one form, the overall safety integrity is a function of these challenges — it is a complex manifestation of the factors described by Turk and Mishra. In another form, the challenge of compliance adherence remains a major threat, with its associated situational manifestations as noted by the ASM Consortium.

SMS for Public Safety, Handbook for ESI and GSI Companies [Ref. 10] has outlined what electricity and gas distribution companies should do to create public safety, as well as how they should be complying with jurisdictions and governing standards bodies. The

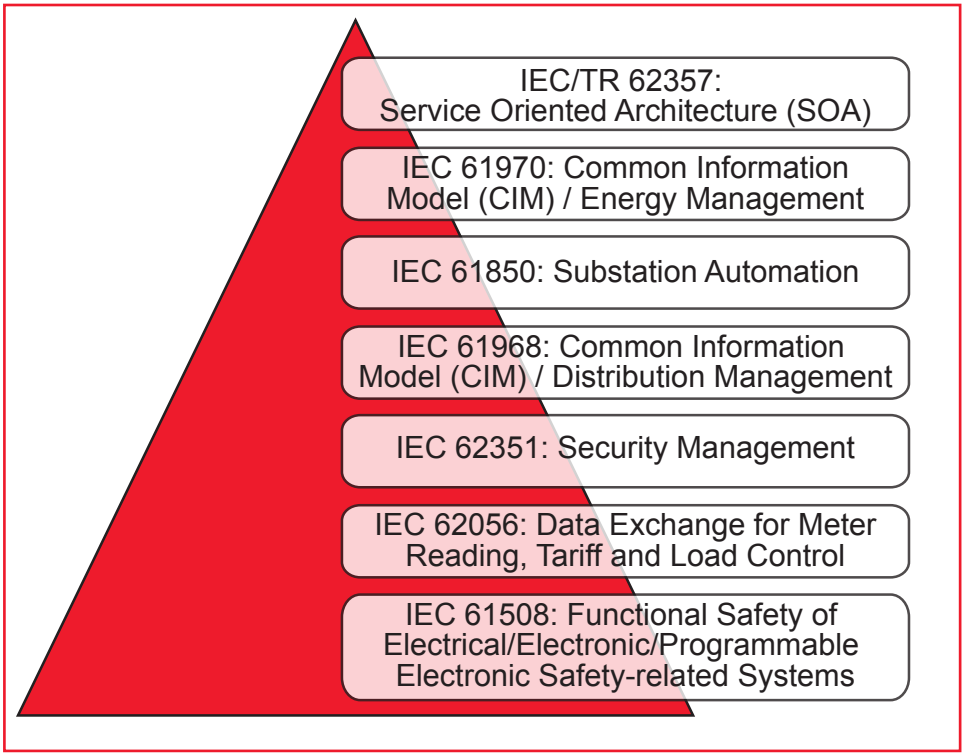


*Figure 11 — Smart Grid Interoperable Framework.*

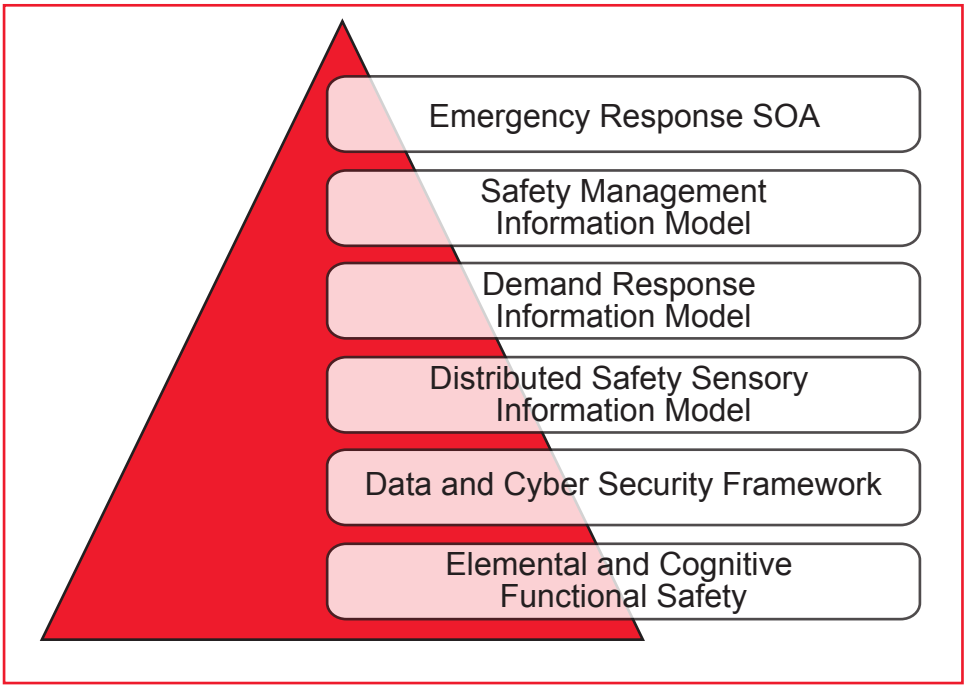


*Figure 12 — Safety Grid Interoperable Framework.*

handbook also explains the implementation model in one of the distribution companies and its details, as illustrated in Figure 10.

The electrical distribution industry has also seen an effective, functionally safe distribution management system in its evolving Smart Grids. The International Electro-Technical Commission (IEC) has standardized the various models for Smart Grids, as illustrated in Figure 11. Desirable properties of public safety networks [Ref. 11] detailed the various needs and requirements of this new generation network. The IEC also puts forth the idea of a Public Safety Interoperability Panel (PSIP), which is similar to the Smart Grid Interoperability Panel (SGIP) illustrated in Figure 12. In ongoing research, a Public Safety Communication System similar to the Smart Grid hierarchy was conceived.

In the Public Safety Communication Model (Figure 12), the foundational principles are based on elemental and cognitive functional safety models, as the next generation of public safety is a socio-technical system. These accident models emphasize the cognitive aspects, while the functional resonance model and the STAMP model focus on the theory of constraints for the accident occurrence. The basic functional safety model uses probabilistic models such as FMEA and FTA techniques, as well as hazard analysis techniques like hazard and operability study (HAZOP), as low as reasonably practicable (ALARP), etc.

The safety management information model layer represents the Health, Safety, Environment and Quality (HSEQ) models similar to those described in the industrial world. As next-generation public safety communications are conceived in flat-IP networks, it is important to have layers of communication protection, including cyber-security. Emergency response service-oriented applications form the last layer of protection to combat disasters, with this layer assisting in disaster preparedness. The two other layers include the distributed sensor management layer and the demand response layer, which act as information providers to consumers in the safety loop.

Ongoing research in public safety communications is focused on emergency management systems.

This research helps direct other systems that help in addressing the challenges in safety management systems.

## Conclusion

The process of designing communication and public safety systems begins with an analysis of use cases put forth by the Public Safety Research Group, which can effectively be used to describe the wireless communication characteristics required by an LTE network. Soon, the holistic role of the communication systems in the overall safety lifecycle of a public safety organization must be accommodated in the systems design phase. The proposal put forth by California's Public Safety Department to realize the public safety system as a system of systems design, along with the New Zealand Energy and Gas Distribution Association's Safety handbook's requirements to cover the entire lifecycle, and the recent disasters in the city of West, Texas indicate the need for communication systems design to cater to other areas of safety management as well. The approach of building a public safety system similar to an enterprise-process safety system comes to light above and it would be critical for the communication systems design to aid in overcoming the existing challenges in process safety management systems.

## About the Authors

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He has authored nearly 25 invention disclosures in the areas of life safety, critical infrastructure protection and situational awareness. Aanandh has published two conference journal papers in chaotic cryptography and measurement instrumentation for yarn quality testing. He is also the recipient of Honeywell's Global Technical Excellence Award.

**Dr. Chinmaya Kar** holds a bachelor's degree in mechanical engineering, a master's degree in industrial engineering and management, and a Ph.D. in mechanical engineering. He has 11 years of research experience at various organizations, including Honeywell ACS Advanced Technology Lab, General Electric Global Research, INSA (Lyon, France), Crompton Greaves Limited and IIT Kharagpur, along with seven years of teaching experience. His interests include, among other things, reliability analysis and condition monitoring, as well as data analytics (such as decision support system, signal processing, statistics, etc.). Currently, he is a Honeywell Fellow at Honeywell Technology Solutions, where he is leading initiatives of condition monitoring and the Internet of everything. Dr. Chinmaya is collaborating in various initiatives on products/prototypes such as Asset Manager, Equipment Health Monitoring, Idler Monitoring, Compressor Blade Health Monitoring, etc. He is leading global projects such as WiBRATE (under the European Commmision's FP7 grant) and Idler Monitoring under these initiatives.

Chinmaya has authored nearly 20 publications in various journals and at conferences, holds 13 patents, two provisional patents, three trade secrets and nearly 36 disclosures (reports). He is a recipient of Erasmus Mundus Fellowship from European Commission and High-Value Ph.D. Fellowship from IIT, Kharagpur. He has also received several awards from Honeywell and GE — notably the annual Prolific Innovator award from Honeywell in 2012 and a management award from GE in 2007. He is a reviewer of journals such as *IEEE Transaction on Industrial Electronics*, *Mechanical Systems and Signal Processing*, *Journal of Sound and Vibration*, and *Journal of Vibration and Control*. He chaired sessions at the International Conference of CM/MFPT 2013, held in Poland. He is a certified vibration analyst Cat III and has certification in Six Sigma DFSS greenbelt. He has delivered a number of invited talks at different organizations.

**Dr. Nihal Siddiqui** completed his post-graduate work in environmental science and a doctorate in environmental biology. In addition, he also holds an industrial safety and post-graduate diploma in environmental impact assessment. The topic of his research was environmental impact assessment. Dr Siddiqui specializes in the area of environmental pollution, environmental monitoring and control techniques, and disaster management. He is currently associated with the University of Petroleum & Energy Studies, Dehradun, as the head of the Health Safety and Environmental Engineering Department. He was also associated with the Health, Safety and Environment Department of ICEM college, Muscat, Oman  University of Central Lancashire, U.K.

He has more than 65 research papers to his credit and has participated in several national and international conferences. Dr. Siddiqui has authored two books — *Environmental Management Systems and Natural Resources* and *Handbook on Fire and Safety*. Dr. Siddiqui has guided more than 50 M.Tech and seven Ph.D. theses.

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