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Resilience metrics for improved process-risk decision making: Survey, analysis and application

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ABSTRACT

The use of metrics in risk assessment and management of chemical process systems is a well-known area of research. There are numerous sources, which provide a comprehensive list of such metrics categorized into leading or lagging and technical or social. However, the significance of these metrics to overall risk and resilience assessment of the system is not well established. Process Resilience Analysis Framework (PRAF) is an advanced method of risk assessment with three phases – avoidance; survival; and recovery, which include twenty-four resilience metrics covering both technical and social factors. In this paper, we are reporting on the statistical analysis of the resilience metrics survey conducted within the process industry. The survey respondents present a wide variety of experience and employment sectors. This paper aims to answer the following three research questions related to resilience metrics– what are the most important metrics for each of the 3 phases?; are there any differences in viewpoints of various groups of survey respondents?; and what is the relative level of importance for each of the metrics? Answers to these research questions are critical in the quantification of overall process resilience and also provide the essential information for senior management to make informed risk decisions. Therefore, a PRAF survey based on Likert type questionnaire was conducted, which produced categorical responses. Methods and techniques such as ordinal alpha, Kruskal-Wallis test, and polychoric correlations, relevant to analyze categorical responses have been used in the programming language R.

1. Introduction

In recent years, there has been an increase in the research literature on the application of resilience concepts in enhanced risk assessment and management (Francis and Bekera, 2014; Steen and Aven, 2011). Various researchers have defined 'resilience' in different contexts and viewpoints as presented in Table 1.

It was in 2004 when Hollnagel, Woods, and Leveson introduced the concept in terms of technological safety by stating that resilience engineering is a paradigm to safety and can be used to avoid human and organizational failure. The definition by Jackson (2009) is closely related to process system resilience. They define resilience, as "the intrinsic ability of a system to adjust its functioning prior to, during or following changes and the disturbances, so that it can sustain required operations under both expected and unexpected conditions". This definition obviously comprises the definition of safety, as 'ability to sustain required operations' and is equivalent to freedom from unacceptable risks. However, resilience emphasizes the ability to function in both expected and unexpected conditions rather than just to avoid failures. Also, an anticipation element is included with the use of words 'prior to' in the definition. Resilience analysis is distinguished from risk assessment in several ways. Principally, conventional risk assessment methods are used to determine the negative consequences of potentially undesired events and to mitigate them. Based on work by Dekker et al. (2008) and Jain et al. (2018) in contrast, the resilience approach emphasizes an assessment of the system's ability to anticipate, survive and recover.

It is only since the BP Texas City Refinery incident in 2005, that the need for process safety indicators has gained momentum. Primarily two types of process safety metrics have been defined in literature – leading and lagging. Recent investigations discovered that consideration of only lagging indicators over leading indicators is not a good practice. Lagging indicator data might be useful for organizational benchmarking purposes, however, it lacks the potential of enlightening the management on the true process safety statistics and safety culture. Several works have been undertaken to develop approaches using metrics. (Tugnoli et al., 2012) discussed an approach for the inherent safety metric and demonstrated its application through comparison of

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Table 1
Resilience definitions.

Year	Definition	Area	Reference
1973	A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.	Socio-ecological systems	Holling (1973)
1999	Disaster resilient community is a community that can withstand an extreme event (natural or manmade (with a tolerable level of losses (and is able to take mitigation actions consistent with achieving that level of protection.	Disaster resilience	Mileti (1999)
2004	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function (structure (identity and feedbacks.	Socio-ecological systems	Walker et al. (2004)
2006	Ability to recognize & adapt to handle unanticipated perturbations that call into question the model of competence (and demand a shift of process (strategies and coordination.	Organizational system	Fujita (2006)
2006	A balance of stability and flexibility that allows for adaptations in the face of uncertainties without losing control.	Organizational system	Grote (2006)
2006	The ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently or to deliver essential services.	Economic systems	Perrings (2006)
2006	The capacities for an enterprise to survive (adapts (and grow in the face of turbulent change.	Economic systems	Fiksel (2006)
2006	The loss and loss recovery required maintaining the function of the system with minimal disruption.	Seismic resilience	Cimellaro et al. (2006))
2006	The ability of an organization to cope with unexpected and unplanned situations and respond rapidly to events (with excellent communication and mobilization of resources to intervene at critical points. It also includes the characteristic of managing the organization's activities to anticipate and circumvent threats to its existence & primary goals.	Safety systems	Hale and Heijer (2006)
2007	The maintenance of positive adjustment under challenging conditions such that the organization emerges from those conditions strengthened and more resourceful.	Organizational system	Vogus and Sutcliffe (2007)
2007	The ability of a system to recover from adversity (either back to its original state or an adjusted state based on new requirements; building resilience requires long-term effort involving reengineering fundamental processes (both technical and social.	Critical infrastructure systems	McCarthy (2007)
2011	The ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.	Safety systems	Aven (2011)
2012	The capacity to manage shifts between attractors for the purpose of preserving an infrastructure service.	Critical infrastructure systems	Bollinger and Dijkema (2012)
2012	The ability to bounce back when hit with unexpected demands.	Safety systems	Dinh and (2012)

Table 2
Selected list of works on process safety or risk management metrics.

Sources	Process safety or risk management metrics
HSE and Association (2006)	Guidelines to develop process safety indicators
CCPS (2007)	Description and use of Process Safety Leading and Lagging Metrics
OECD (2008)	Comprehensive document providing guidance to assist industry public authorities and communities to prevent and prepare for chemical accidents
API (2010)	Standard API RP 754: Process Safety Performance Indicators for the Refining and Petrochemical Industries
IOGP (2011)	Report on Process Safety: Recommended Practice on Key Performance Indicators
Wang et al. (2013)	New normalization factors for process safety lagging metrics
Petroleum Safety Authority (2015)	Two categories for major hazard risk indicators within the oil and gas industry: precursor events and barrier elements
Swuste et al. (2016)	Various indicators are reviewed to answer which indicators qualify to provide insight and knowledge in levels of safety of processes or business

Table 3
List of works on resilience metrics.

Authors	Metrics or principles or elements of resilience
Wreathall (2006)	Seven themes of Highly Resilient Organizations (HROs): Top-level commitment (just culture (learning culture (awareness (preparedness (flexibility (and opacity
Hollnagel (2009)	Four cornerstones of Resilience Engineering (RE): Anticipate (monitor (respond (and learn
Costella et al. (2009)	Four principles: Top management commitment (flexibility (learning (and awareness
Øien et al. (2010)	Eight Contributing Success Factors (CSFs): Risk understanding (anticipation (attention (response (robustness (resourcefulness/rapidity (decision support (and redundancy
Tveiten (2012)	Three elements for emergency management: Proactive emergency management through early risk anticipation (emergency management's adaptation to new and future work practices such as distributed actors (and emergency management's adaptation to new and future work practices such as new technology
Dinh et al. (2012)	Six principles: Flexibility (controllability (early detection (minimization of failure (limitation of effects (and administrative controls/procedures
Azadeh (2014)	Integrated Resilience Engineering (Tveiten et al.) Factors: Self-organization (teamwork (redundancy (and fault-tolerant
Jain et al. (2017. 2016)	Process Resilience Analysis Framework Four resilience aspects: Early detection (error tolerant design (recoverability (and plasticity Twenty-four process system resilience metrics

LNG regasification technologies. (Khan et al., 2010) established the risk-based process performance indicators for improving the existing safety performance indicators. There are numerous sources, which provide a comprehensive list of such metrics categorized into leading or lagging and technical or social. Table 2 summarizes some of the selected works on process safety or risk management metrics existing in the literature. It is important to note that resilience emphasizes human and organization aspects, as well as technical aspects. Table 3 lists some