Improving the Robustness and Resilience Properties of Maintenance

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Abstract

Industries with major accident potential, e.g. the process industries, are usually characterized by high degree of technological and organisational complexity, and hence are fortified with layers of protection (barriers). The energy-barrier risk control model is dominant and tends to be applied by such industries over time, sometimes without paying attention to the vulnerability of the complex organisational setting encompassing production, maintenance, support and the environment. In the same vein, process industries may prioritize production at the expense of safety systems and the organisational network. Maintenance is known to be a key means of keeping safety systems functional, yet, in this paper we wish to explore how its values can be further uncovered to improve the robustness and resilience of the socio-technical system as a whole.

This paper intends to investigate what robustness and resilience properties exist in maintenance and how these can be improved in relation to maintenance interaction with other areas such as production and support and in turn improve the robustness and resilience of the process industries organisation. The objective is to improve the robustness and resilience of the organisation as a whole. This is realized on the basis of the perspectives of organisational accidents: Energy-barrier model, normal accident theory (NAT), high reliability organisations (HRO) theory, man-made disaster (MMD) theory, conflicting objectives, adaptation and drift (COAD) theory and resilience engineering. Based on this, recommendations for improving the maintenance robustness and resilience were proposed.

Keywords: Maintenance, Robustness, Resilience, Organisation, Organisational accident, Process industry

1. Introduction

The purpose of maintenance is to retain systems in or to restore them to a functioning state. Maintenance also contributes to improved system knowledge and inter-discipline coordination that may benefit the entire organisation. This may indicate that maintenance may be a contributor to robust and resilient organisations and systems whose ability to prevent or limit unexpected events is improved. It is therefore of interest to investigate how maintenance can be performed to gain this "added" value of increased organisational robustness and resilience.

Industries with major accident potential, e.g. the hydrocarbon and chemical process industries, are usually characterized by high degree of technological and organisational complexity (Okoh and Haugen, 2013a,b). It is common practice in such industries to install layers of independent safety barriers that are capable of preventing the occurrence or mitigating the consequences of unexpected events in accordance with the energy-barrier principle (Gibson, 1961).

The energy-barrier principle is dominant among the organisational accident perspectives (Rosness et al., 2010; Okoh and Haugen, 2012) and tends to be applied by high-risk industries over time. Focus is often on technical issues, sometimes without paying attention to the vulnerability of the complex organisational setting encompassing production, maintenance, support and the environment. In the same vein, process industries may prioritize production at the expense of safety systems and the organisational network. This was the case in the Texas City refinery explosion (CSB, 2007; Okoh and Haugen, 2014c) and the Macondo blowout (SINTEF, 2011). The safety and production objectives of industries cannot be realized to the fullest without the personnel relating appropriately and adequately with each other, the environment and the systems. The application of a suitable combination (a mix of both the technologically and organisationally biased) of the accident perspectives can improve safety significantly (Pitblado, 2011; Rosness et al., 2010; Okoh and Haugen, 2012).

Several authors have highlighted the importance of maintenance to physical asset management and suggested ways to improve maintenance in relation to improved dependability of the assets (Okoh, 2010; Ø ien et al., 2010; Wilson, 2002). However, the potential of maintenance to improve the robustness and resilience of the organisation itself has yet to be uncovered. The hypothesis is, by virtue of its interaction with the other departments and the environment, maintenance could also improve the robustness and resilience of the organisation, not only systems.

Some studies have been done on robustness (Anderies et al., 2004; Nielsen and Holmefjord, 2004; Boissieres and Marsden, 2005; Pavard et al., 2007). Few of them have analyzed organisational robustness in relation to organisational accident (Nielsen

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and Holmefjord, 2004) or maintenance (Boissieres and Marsden, 2005). The latter focused on the telecommunications industry, whereas the former focused on a hydrocarbon industry's emergency preparedness organisation - a subset of the entire industrial organisation. However, this paper will explore the process industry organisation from a broader perspective. Various industrial sectors are characterized by different configurations of independent and coordinated units aimed at realizing the set of organisational goals. It is important to address this situation specifically to achieve a better solution for a given industry.

In this paper, we intend to investigate what robustness and resilience properties exist in maintenance and how these can be improved in relation to maintenance interaction with other areas such as production and support and in turn improve the robustness and resilience of the process industries organisation. The methodology is based on the application of the six perspectives of organisational accidents, i.e., energy-barrier model, normal accident theory (NAT), high reliability organisations (HRO), man-made disaster (MMD) theory, conflicting objectives, adaptation and drift (COAD) theory and resilience engineering (Rosness et al., 2010). Several of the perspectives focus on how accidents are not caused only by technical failures of physical systems, but in some cases by human and organisational factors or a combination of these. Hence, it is pertinent to investigate the maintenance-related contribution to organisational robustness and resilience in light of these factors. The contribution of maintenance to the organisational robustness and resilience will be derived by mapping the factors that influence robustness and resilience (according to each of the organisational accident perspectives) to the links between maintenance and production, maintenance and support, and maintenance and the environment. The paper will focus on the hydrocarbon and chemical process industries.

The rest of the paper is structured as follows: (2) The concept of robustness and resilience: This section will define robustness and resilience and present various views about organisational robustness and resilience from different authors, (3) Organisational composition of process industries: This section will analyse the structure of the industry and the associated dependencies, (4) A typical maintenance work process: This section will describe a maintenance work process applicable to the hydrocarbon and chemical process industries, (5) Investigating robustness and resilience properties in maintenance: This section will ascertain whether and what robustness and resilience properties are obtainable from maintenance, and (6) How the robustness and resilience of maintenance and the organisation can be improved: This section will investigate how the robustness and resilience of maintenance and the organisation can be improved in relation to maintenance interaction with production, support and the environment, and (7) Conclusion: This section will present a summary of the findings.

2. The concept of robustness and resilience

Robustness is the noun form of the English adjective "robust" which originates from the Latin "robustus" - it simply means firm, hard, strong. However, in scientific use there are different definitions of robustness (Jen, 2005), and as yet, there is no universally accepted definition. There may never be a unified definition, because different disciplines may choose to use the term differently, so we have to be careful about choosing definitions from very different applications. Besides, robustness tends to be misconstrued for resilience sometimes (Pavard et al., 2007).

Robust systems, according to Asbjørnslett and Rausand (1999), are characterized by (i) resistance to accidental events, (ii) restoration of functionality and (iii) retention of original stability (Asbjø rnslett and Rausand, 1999). This view is consistent with that of Ferdows (1997) - "The ability to cope with changes in the competitive environment without resorting to changes in the structure" (Ferdows, 1997) and that of Chandra and Grabis (2007) - "The ability to withstand external and internal shocks" (Chandra and Grabis, 2007). As viewed by Agarwal (2007), a system is robust if it does not yield to any damage characterized by significant loss of form and function, and even a single mode of vulnerability renders a system unrobust no matter whether the system is acceptable under other kinds of demand (Agarwal et al., 2007). Furthermore, robustness as seen by Pavard (2007) is the ability of a system "to adapt its behaviour to unforeseen situations, such as perturbation in the environment, or to internal dysfunctions in the organisation of the system" (Pavard et al., 2007).

Resilience as defined by Foster (1993) is "the ability to accommodate change without catastrophic failure, or the capacity to absorb shocks gracefully" (Foster, 1993). According to Asbjørnslett and Rausand (1999), it is characterized by transition to a new stable situation after the unexpected events, and this is consistent with that of Woods(2006a) - a quality encompassing "monitoring the boundary conditions of the current model for competence (how strategies are matched to demands) and adjusting or expanding that model to better accommodate changing demands" (Woods, 2006a). Furthermore, resilience is also seen by several other authors in the following ways:

According to Hollnagel (Hollnagel, 2011): Resilience is "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions". He points out that the engineering of resilience is dependent on the application and management of "the ability to respond to events, to monitor ongoing developments, to anticipate future threats and opportunities, and to learn from past failures and successes alike".

As stated by Hollnagel and Sundström (Hollnagel and Sundström, 2006): "A resilient system, or, organisation is able to withstand the effects of stress and strain and to recover from adverse conditions over long time periods".

In the opinion of Pariès (Paries, 2011): Resilience is "a combination of readiness and creativity, and of anticipation and serendipity", implying being prepared both for the expected and the unexpected. He also classifies resilience into two: (1) resilience features designed into a system as a whole and (2) resilience features of the elements or the agents (e.g. human agents) that interact with the system. He views the systemic resilience as emerging from the interaction of individual agents' behaviour, and the resilience of the individual agents themselves as being partially influenced by the systemic resilience, emphasizing that the best strategy is a waste if it cannot be implemented by the skillful operators at the "sharp end" of the system. Besides, Pariès (2011) suggests a hierarchical "defence in depth" strategy as a means of achieving the combination of anticipation and serendipity, such that a failure in a line of defence activates "a tactical retreat behind the next one, with operating procedures shifting from detailed protocols for normal situations, to a generic action framework for emergency situations."

As indicated by Woods (Woods, 2011): A resilient system can be seen as a system with the quality of ascertaining whether the current adaptive capacity is enough to meet future demands, implying that an insufficiency of this quality makes the system vulnerable to sudden collapse and failures. He suggests the following as patterns of anticipation: (1) Being "able to recognise that adaptive capacity is falling", (2) being able to identify "the threat of existing buffers and reserves", (3) being "able to recognise when to shift priorities across goal tradeoffs", and (4) being "able to make perspective shifts and contrast diverse perspectives that go beyond their nominal system condition".

In the view of Leveson et al. (Leveson et al., 2006): Leveson et al. classify resilience into reactive resilience and preventive resilience. According to them, the former involves "the ability to continue operations or recover a stable state after a major mishap or event", whereas the latter involves the "ability of systems to prevent or adapt to changing conditions in order to maintain (control over) a system property".

Quoting from McDonald (McDonald, 2006): "Resilience represents the capacity (of an organisational system) to anticipate and manage risk effectively, through appropriate adaptation of its actions, systems and processes, so as to ensure that its core functions are carried out in a stable and effective relationship with the environment".

On the authority of Wreathall (Wreathall, 2006): "Resilience is the ability of an organisation (system) to keep, or recover quickly to, a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses". He suggests that financial or other important goals should also be considered in addition to safety which is often focused on.

The African elephant and the hydra can serve the purpose of analogies for robustness and resilience respectively. The elephant is sturdy enough to bulldoze its way through trees without succumbing to deliberate and accidental impacts - this demonstrates robustness. In the case of a hydra, if the body is bisected horizontally, the upper half will develop a new foot and the lower half will develop a new head (Galliot and Chera, 2010). Being bisected can be seen as an accidental event to the hydra, the bisected state can be seen as an unstable state of the hydra, and the regenerated state consisting of two new hydras can be seen as a new stable state; this is demonstrative of resilience. A hydra with the head and foot both severed will also grow a new head and new foot (Galliot and Chera, 2010), showing a transition from a stable state with a head and a foot both intact, through the interaction with the accidental event (the instance of being cut off), through an unstable state with no head and foot, to a new stable state characterized by regenerated structure - this also demonstrates resilience.

Vulnerability is a key term that is sometimes taken to mean the opposite of robustness or resilience. Hence, it is relevant to delineate vulnerability as well. Vulnerability, in the context of Agarwal (2007), indicates a potential to experience consequence which is disproportionately large compared to the amount of damage or perturbation causing it. However, vulnerability according to Asbjørnslett and Rausand (1999), refers to "the properties of ... a system that may weaken or limit its ability to endure threats and survive accidental events that originate both within and outside the system boundaries." Similarly, NS 5814:2008 defines vulnerability as "the inability of an object to resist the impacts of an unwanted event and to restore it to its original state or function following the event" (NS5814, 2008). Furthermore, ISO Guide 73:2009 defines vulnerability as "intrinsic properties of something resulting in susceptibility to a risk source that can lead to an event with a consequence" (ISO, 2009).

Robustness, as applied in this paper, is the ability to resist or counteract accidental events. Furthermore, resilience, as applied in this paper, is about being able to adapt to or recover from accidental events, while stability is acquired in a new state.

In light of the potential for accidental events in the process industries and how the effects can be resisted or counteracted by an organisation or how an organisation can adapt itself to or recover from them, we can, as will be demonstrated later, investigate maintenance contribution to organisational robustness and resilience by using the various perspectives of organisational or major accidents.

In order to analyse how the robustness and resilience properties of maintenance can be improved in relation to other departments within the process industries, it is necessary to define typical organisational components, their boundaries and how they interact with each other (internal) and with the environment (external). This will be covered in the following section.

3. organisational composition of the process industries

We may consider the hydrocarbon or chemical process industry as an organisation or socio-technical system characterized by "interaction between the technical structure of the system and the social and organisational structure of the operators who run the system" (Boissieres and Marsden, 2005).

The organisation can be seen as a system consisting of three elements, i.e., production, maintenance and support

Wilson (2002). Figure 1 depicts the relationships between the various elements of this system and the environment.

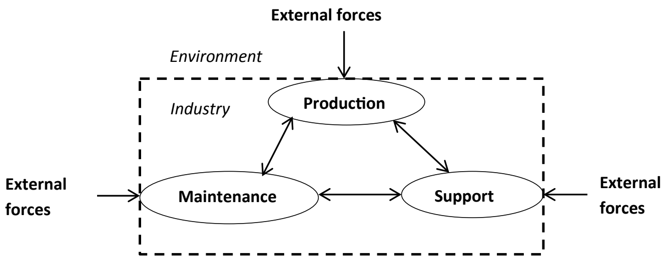

Figure 1: A conceptual model of an industrial organisation

According to Figure 1, the opportunities for maintenance to realize improved robustness and resilience properties within the process industries are shown in the following links: (1) The link between maintenance and production, (2) The link between maintenance and support and (3) The link between maintenance and external forces. The links represent means by which maintenance can interact in harmony with other elements. These relationships at the elemental level will contribute to realizing the organisation's goals (Rescher, 2005).

3.1. The Link Between Maintenance and Production

Maintenance and production are functions whose relationship with each other are critical to the success of a producer organisation (Swanson, 1997; Duffuaa, 1995; Jonsson, 1997). A weak link between them can lead to economic loss in repairs and downtime or increased risk to personnel and the environment (Okoh, 2010). Some examples of likely sources of failure include: (i) production staff overusing machines, thus affecting maintainability, (ii) maintenance team not getting data (such as equipment runtime) requested from the production team, (iii) production being in charge of maintenance, and (iv) maintenance staff blaming its ineffectiveness on production not providing adequate budget, accessibility and cooperation.

There is the need for both production and maintenance departments to strive for a common goal - plant profitability. This goal is the basis for continuous existence of both. Maintenance cannot survive in isolation without budget from production and production cannot generate substantial revenue from the customer/market without the guarantee of uptime by maintenance (Duffuaa, 1995). To achieve the production objectives, the maintenance strategy should not necessarily be fixed but depend on the dynamics of the business climate. In order to reduce production cost due to equipment failure, a company may choose to do maintenance optimization or go for renewal. In the same vein, to reduce production cost for other reasons, a company may consider Total Productive Maintenance (TPM), maintainability improvement etc., which requires cooperation between maintenance, production and/or support (Swanson, 1997). In the case of TPM, there is substantial evidence that it is being applied to a large extent by refineries in Japan and Saudi Arabia (JCCP, 2009a,b, 2012), although the original focus of the method was the manufacturing industry.

In addition, the production and maintenance staff have to cooperate to achieve the organisation's safety objective which contributes to the overall business objective. There is the need for the production staff to make adequate preparations for maintenance (Okoh and Haugen, 2014a), e.g., by ensuring that residual hazardous materials are evacuated from equipment to be maintained and by selecting and securing isolation points, and so on (Wallace and Merritt, 2003). Computerized Maintenance Management System (CMMS) and Permit To Work (PTW) systems are some tools that can facilitate coordination and communication between maintenance and production.

3.2. The Link Between Maintenance and Support

Support for maintenance is critical to the performance of maintenance activities and it constitutes a parameter for measuring the effectiveness of maintenance. It is important for maintenance personnel to be supported also by personnel other than production personnel when called upon, e.g. by Information Technology (IT) personnel. According to (EN 13306, 2010), maintenance supportability is "the ability of a maintenance organisation to have the correct maintenance support at the necessary place to perform the required maintenance activity when required".

A maintenance support system may consist of (i) sensors on production equipment which help to prevent unplanned downtime by alerting maintenance personnel on time about equipment failure modes, (ii) a computerized maintenance management system (CMMS) which enables maintenance personnel to organize maintenance activities efficiently, (iii) radio frequency identification (RFID) devices which enable ease of identification of spare parts in a store, (iv) electronic permit to work systems (e-PTW) which promotes safety management, (v) emergency response team for crisis management, and so on. These systems require information technology support to be regularly functional. Supply and logistics are other forms of support for maintenance.

3.3. External Forces on Maintenance

Maintenance performance can be hindered by external forces such as concurrent activities in neighboring sites and severe weather conditions (e.g. winter or arctic conditions), and the negative impact will translate to production and safety limitations. The arctic environment, for e.g., can increase equipment failure rates, failure modes and failure mechanisms, thus necessitating increased diversity and frequency of preventive maintenance in addition to increased frequency of corrective maintenance (Homlong, 2010). Exposure to cold is another factor that is unfavorable to the maintenance crew with its attendant effects on work performance, occupational health and quality (ORIOH, 2001).

Other forms of external forces such as regulatory oversight (e.g. deficiencies in standard/safe operating procedures for maintenance), legislation (e.g. phasing out a given repair technology), disputes (e.g. with environmental activists, host communities, trade unions etc.), government policies (e.g. exorbitant duties on tools, materials or spare parts), market dynamics (e.g. price fluctuation of tools, materials or spare parts) and technological advancement (e.g. leading to obsolescence of spare parts) can also influence maintenance.

3.4. Final comment

In addition to the knowledge of the kind of interactions that exist between maintenance and the other aforementioned units within a process industry organisation, it is important to understand the maintenance work process itself since such interactions will actually take place in relation to the various phases of the maintenance work process. Hence, the following section will be used to describe a typical maintenance work process in the process industries.

4. A typical maintenance work process

The maintenance work process in the process industries may vary depending on the situation of the plant, whether the decision to maintain a part of or the whole plant is being taken at the time the item is in service or out of service.

If an item in service requires maintenance, it can be shut down before maintenance or maintenance can be carried out while it is still in service. If an item requires shutdown for maintenance, the organisation may follow a maintenance work process as shown in Table 1. If an item is already inoperative, the same process applies except for shutdown.

The phases of the maintenance work process presented in this section can be seen as the various aspects of maintenance that can be influenced by the other organisational units (i.e. production and support) and they will be used as a basis for investigating the improvement of the robustness and resilience properties of maintenance in relation to production and support as will be seen later.

Table 1: Definition of the maintenance work process elements

Maintenance Work Process Elements	**Definition**
Planning/ Scheduling/ Failure diagnosis	Planning is the organisation and documentation of a set of tasks that include the activities, procedures, resources and time scale required to carry out maintenance, whereas scheduling is the predetermined detailing of when a specific maintenance task should be carried out and by who (EN 13306, 2010). Failure diagnosis refers to actions taken for fault detection, fault localization and identification of causes (EN 13306, 2010).
Mobilization/ Shutdown	Mobilization is the supply, movement and deployment of resources. Shutdown is outage implemented in advance for maintenance, or other purposes (EN 13306, 2010).
Preparation for maintenance work	Provision of required information and applying the requirements (e.g. Permit to work-PTW, Lockout/Tagout-LOTO procedure, hazardous material evacuation, securing of isolation points etc.) that will enable maintenance to be performed effectively and safely.
Performance of the maintenance work	Hands-on actions taken to retain an item in or restore it to a state in which it can perform its required functions.
Startup	A state in which a maintained item is being made "live", i.e. the item is being activated or actuated.
Normal operation	A state in which an item is in service.

5. Investigating robustness and resilience properties in maintenance

In this section, the intention is to investigate, based on the organisational accident perspectives, what robustness and resilient properties are obtainable from maintenance. The organisational accident perspectives present bases for organisational accident causation. Besides, maintenance is known to be a key contributor to organisational accident prevention. Hence, it is possible for maintenance to possess certain qualities implied in the perspectives by which organisational accidents may be prevented. This is a hypothesis that will be tested in the following. We will first describe the organisational accidents perspectives, analyse their significance to maintenance and then identify the robustness and resilience properties in maintenance.

5.1. Description of the organisational accident perspectives

The energy-barrier perspective: The energy-barrier perspective, which is based on the hazard-barrier-target model of Gibson (Gibson, 1961), depicts a linear progression of events from the release of energy (hazard) through supposedly interposed barriers to the interaction between the energy (hazard) and the target (victim). The model is hinged on the concepts of linearity and monocausality, i.e., the transfer of a given energy from the source to the target. This model also forms the basis for Reason's Swiss Cheese Model (Reason, 1997) and the "defence in depth" principle. An example of how this has been institutionalized in risk management can be found in the Norwegian regulations for offshore installations, where a separate section in the Management Regulations is dedicated to barriers (PSA, 2010). The model basically has three main risk control strategies: (1) Control of the hazard, (2) Control of the barrier, and (3) Control of the target's situation/condition.

The normal accident theory (NAT): The normal accident theory (NAT), proposed by Perrow (1984), expresses the concept of accident proneness (i.e natural tendency towards accidents) owing to the interactive complexities (technological and organisational) and tight couplings that evolve as our world of technologies continue to expand (Perrow, 1984). The Normal accident perspective is hinged on complexity and multicausality. Perrow (1984) believes that the multiple barriers and redundancies that characterize such high-risk technologies (which are being managed on the premise of the energy-barrier model) could offer some level of safety, but will subsequently increase the system's degree of complexity and tightness of couplings. Complexity and coupling are not very precise terms (Hopkins, 1999), but being able to delay processing time is an example of loose coupling, while the opposite is a tight coupling (Perrow, 1984). According to Gell-Mann (Gell-Mann, 1994), "as the list of regularities characterizing a given system's operation increases, that system becomes more complex." It can be inferred that the simpler we keep our technologies, the safer we are bound to be, and this is the basis for Perrow's conclusion that certain technologies should be scrapped in their current composition because we cannot think of any organisation that has the capacity to sufficiently control them. The reason for this is that Perrow (1984) claims that a system of interactive complexity can be effectively controlled only by a decentralized organisation and a system of tight couplings can be effectively controlled only by a centralized organisation, thus making it impossible to devise an organisation that can control the system effectively. The policy reversal in Germany (driven by the Fukushima disaster in Japan) that will see all her nuclear power plants abandoned by 2022 (BBC, 2011) may be seen as a logical and necessary result of NAT. NAT is not a general theory of major accidents since it is limited to specific technologies, those with high complexity and tight couplings. Further, accidents within such systems need not necessarily be classified as normal accidents either. Perrow himself presents numerous examples of this in his book (Perrow, 1984). Criticism of the theory has been raised (Hopkins, 1999) and HRO theorists argue that systems indeed can be both complex and tightly coupled, still having an excellent safety record.

High reliability organisation (HRO) perspective: The HRO theory has been developed from studies of organisations which, according to normal accident theory, should experience major accidents, but which still have excellent safety records (LaPorte and Consolini, 1991). The foremost example used to illustrate this is aircraft carriers, but other organisations, like hospital emergency rooms, have also been studied. A number of technologies we have today have great productive potential and at the same time great destructive potential, such that the avoidance of a significant failure is imperative (LaPorte and Consolini, 1991). These technologies include the high-risk technologies referred to by Perrow (1984) as having interactive complexities and tight couplings, although the HRO perspective expresses the possibility of managing such technologies unlike Perrow's pessimistic position (Rosness et al., 2010; Saleh et al., 2010). An objection to Perrow's pessimism is provided by the HRO perspective in the possibility of switching from centralization during normal operations to decentralization in hazardous situations and consulting expert judgment (Saleh et al., 2010). According to Sagan (Sagan, 1993), HRO organisations inherently possess the best safety records of all high-risk technologies. The characteristics of HROs as identified by several theorists may be summed up in the following: (i) Diligence in failure analysis and organisational learning, (ii) Mutual agreement on production and safety as being concurrent organisational objectives, (iii) Decentralization and centralization of authorities, and (iv) Personnel and technical redundancy (Saleh et al., 2010). HRO theorists believe that through management commitment to safety, the establishment of safety culture, the maintenance of relatively closed systems, functional decentralization supported by constant training, technical and organisational redundancies, and organisational learning supplemented by anticipation and simulation (trial-and-error process), organisations could achieve the consistency and stability required to support failure-free operations (LaPorte and Consolini, 1991; Saleh et al., 2010; Sagan, 1993; Dekker et al., 2008).

Man-made disaster perspective (MMD): The man-made disaster (MMD) theory considers accidents to be the result of accumulated flaws in information processing between various organisational units, including the administrative, managerial and operational units (Turner, 1978). Turner (1978), the initiator of the theory, calls the period of accumulation an incubation period (i.e. a period of maturity). At the end of the incubation period, the perceived organisational quality is unable to co-exist with the accumulated organisational deviations, thus leading to an accident. A key point in this theory is that there exist warning signs within the organisation that could have been used to prevent accidents, if it had been accumulated and communicated in the right way and to the right people. This perspective is hinged on multicausality, for according to Turner (1978), "accidents are neither chance events, nor acts of God, nor triggered by a few events and unsafe human acts immediately before they occur." The concept behind the theory is sociological; it holds that accidents are not just a technological phenomenon (Dekker et al., 2008).

Conflicting objectives, adaptation and drift perspective: The conflicting objectives/goals (or decision-making) perspective was proposed by Rasmussen (Rasmussen, 1997) and considers major accidents to be the result of organisational objectives clashing with each other. The result of this conflict is an organisation in a state of dilemma that may drift over time due to lack of information or inability to balance the objectives correctly. Examples of organisational objectives that may come into conflict include production objectives, safety objectives etc. The basic resource used to drive the realization of these objectives is money and the application of this resource must create a balance between objectives to guarantee the survival of the organisation. The balance between production (economic objective) and protection (safety objective) was also discussed by Reason (Reason, 1997). The concept of adaptation involves tradeoff, i.e. sacrificing one quality or aspect of something in return for gaining another quality or aspect.

Resilience engineering perspective: Resilience engineering describes the ability of organisations to apply the principles of responding, monitoring, anticipating and learning to adapt to or recover from accidental events, while stability is acquired in a new state. The word “resilience” is derived from the Latin word “resilire” (to leap back), and according to Woods (Woods, 2006b), denotes a system’s “ability to recover from challenges or disrupting events.” In (Saleh et al., 2010), the term “recoverability” is considered as a synonym for resilience. In (Hollnagel, 2011), resilience is defined as “the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.” Resilience engineering describes the ability of organisations to achieve ultra-high levels of safety and response to the dynamics of other organisational values (e.g. production, operations, economy etc.) despite complexities, high risks, major accidents, disturbances, disruptions, continuous pressure and change (Rosness et al., 2010; Woods, 2006b). Accidents, according to this perspective, are not the product of normal system malfunction or breakdown, but rather a breakdown in the adaptive capacity necessary to cope with the real world of complexity (Dekker et al., 2008). According to Gell-Mann (1994), the ratio between order and chaos is the critical factor in determining the capacity of a system to adapt successfully to systemic surprises. Adaptive capacity (or adaptability) refers to the ability of individuals and organisations to adjust their performance to the current condition. The resilience engineering perspective encompasses core topics from the five perspectives described earlier; it is a synthesis of ideas bordering on barriers, complexity, conflicting goals and HRO (Rosness et al., 2010; Dekker et al., 2008). The abilities that constitute resilience can be summarized as follows (Hollnagel, 2009, 2011): (1) Anticipation – Addressing the potential: Foreseeing the changing shape of risk, before failure and harm results, (2) Monitoring – Observing the critical: Recognizing how close the organisation is to the safety boundary, (3) Responding – Coping with the actual: Adapting or being flexible to changes, disruptions and opportunities, and (4) Learning – Updating with the factual: Review of performance based on new knowledge.

5.2. The significance of the organisational accident perspectives in relation to maintenance

Energy-barrier in relation to maintenance: The energy-barrier perspective is about establishing barriers (often technical) and ensuring that these barriers remain intact and effective for as long as they are needed. Maintenance will be an important contributor to maintaining the integrity of the barriers. With this realization, focus on maintenance also increases and maintenance will in itself be a key element in managing risk. In the Norwegian offshore industry, it is quite common to have various safety indicators related to maintenance, in particular maintenance on safety critical equipment. An example is “Hours of backlog on maintenance.” Maintenance is also often regarded as a barrier in itself. This perspective will therefore clearly bring out the importance of sufficient and correct maintenance.

NAT in relation to maintenance: Perrow (1984) believes that some accidents are preventable through certain improved factors, including better equipment or the effects of accidents may be possible to minimize or limit to local effects through safety systems. In both of these cases, maintenance will play a role in ensuring that the equipment and safety systems are kept in operating order and with high reliability. However, since accidents are associated with complexity and tight coupling, the focus of risk management will be on reducing complexity and also loosening coupling within the system being considered. This has at least two implications. First of all, regardless of the frequency and quality with which maintenance is performed, it can only contribute to preserve a certain level of safety. Further improvement will not be possible as long as the system has the undesirable properties that Perrow (1984) pointed out. Maintenance can therefore serve only as a safeguard for the individual parts of high-risk systems, but will not ensure the safety of the whole system. NAT has an organisational perspective and maintenance is therefore not central in the same way as for Energy-Barrier perspective. Secondly, it may be argued that maintenance can be regarded as adding complexity to a system because it implies more activities that need to be performed safely, coordinated with other activities and monitored in a suitable manner. Maintenance optimization may also add tight couplings.

HRO in relation to maintenance: HRO is a theory about organisational aspects that covers all levels of the organisation, from top level management (the “blunt end”) to the operators performing the work in the field (the “sharp end”). The focus tends to be on high risk operations which require vigilance and correct performance (aircraft carriers, emergency rooms). One may speculate that there is a potential for developing a culture where the “heroes” are those which run the operations, and where maintenance is seen as a routine activity with less importance. On the other hand, at least two of the characteristics listed above – (i) Diligence in failure analysis and organisational learning and (iv) Personnel and technical redundancy – will also be contributing to put focus on maintenance. HRO organisations are proactive in avoiding failures and this should also extend to ensuring good maintenance, to avoid technical failures.

MMD in relation to maintenance: This perspective focuses on lack of information flow as the cause of accidents. The status of technical systems, including their maintenance status would be an example of the type of information that is relevant in this context. This perspective will therefore contribute to emphasize the importance of ensuring that this type of information is available. The Piper Alpha disaster (Cullen, 1990) is an example of an accident where information about maintenance was not brought to the attention of all who needed to know. However, maintenance performance as such, and in particular the importance of correct performance of maintenance will not be at the centre of attention in this perspective.

Conflicting objectives, adaptation and drift in relation to maintenance: Maintenance is a clear example of an area where there will be conflicting objectives: The saved cost of not doing it versus the (indirect) risk reduction achieved when doing it. Maintenance objectives are a means of achieving production and safety objectives, but sometimes the sharing of maintenance resources between production and safety systems may be disproportional, or the allocation of maintenance resources to both may be inadequate. Reducing maintenance is a typical example of a cost that is reduced as much as possible due to pressures to operate as cheaply as possible. Although this may have a positive impact on at least production in terms of profit in the short term, it may tend to have a negative impact on both production and safety in the medium or long term. Optimizing maintenance is crucial to optimizing production without compromising safety. This perspective helps to highlight potential pressures that may exist to reduce maintenance.

Resilience engineering in relation to maintenance: Since this perspective draws on elements from the earlier perspectives, the conclusions with regard to how maintenance is viewed will also tend to coincide with elements from the earlier discussions, in particular the discussion about HRO theory. Anticipation and learning can both be pointed out as abilities that will rely among others on maintenance and maintenance records as a basis for achieving this. Barrier maintenance is part of this, but not any different from the Energy-Barrier perspective. Monitoring is a question of detecting early warnings and weak signals, of which lack of maintenance may be one of such signals.

Furthermore, according to Grote (Grote, 2011), tools that support the assessment and promotion of the basic requirements for resilience (i.e. responding, monitoring, anticipating, and learning) encompass "training emergency management, handling fatigue of system operators, supporting preventive maintenance, providing better rules for managing conflicting goals, or improving incident reporting".

5.3. Prevention of drift

Hale and Heijer (2006), like Leveson et al. (2006), also recognise two aspects of resilience: Prevention of loss of control over risk and recovery from that loss of control. Based on Rasmussen's model (Rasmussen, 1997) which explains the concept of drift to failure, Hale and Heijer (2006) define the former aspect of resilience as "the ability to steer the activities of an organisation so that it may sail close to the area where accidents will happen, but always stays out of that dangerous area" (Hale and Heijer, 2006). This, according to them (Hale and Heijer, 2006), implies knowing where an organisation stands in relation to the danger area and activating efficient and effective response when indications of impending or actual danger are detected. Drifting into failure, itself, as explained by Dekker (2006), is "a metaphor for the slow, incremental movement of systems operation toward (and eventually across) the boundaries of their safety envelope" (Dekker, 2006).

One way of preventing maintenance-related drift is by avoiding maintenance postponement of safety-critical elements. An instance where postponement could be forced on maintenance is when a company wants to continue production to satisfy a time-based demand of a customer rather than lose the order to its competitors. If this happens repeatedly, the company will continue to drift towards the edge/boundary of their safety envelope and eventually experience an accident.

Drift is also indicative in accumulated errors in maintenance-related decision making, e.g. accumulated errors in P-F (potential failure - functional failure) interval determination, critical spare parts management, maintenance task selection or maintenance interval determination. This can be prevented by using effective maintenance management tools.

The potential of maintenance to expose its personnel to major hazard facilities and to introduce new hazards, new failures and initiating events for accident scenarios will increase with increasing frequency (i.e. reducing interval) of maintenance. This implies an increasing annual risk (i.e. probability of fatality per hour x maintenance duration in hours x number of maintenance intervals in a year x number of personnel exposed) and a drift to failure. A way to prevent this is to optimize maintenance intervals in terms of risk with the objective of minimizing the maintenance-related major accident risk.

5.4. Final comment

Based on the aforementioned analysis, we have identified and defined some maintenance-related robustness and resilience properties in relation to the organisational accident perspectives and these are shown in Table 2.

6. How the robustness and resilience of maintenance and the organisation can be improved

In Tables 3 and 4, the steps in the maintenance process have been combined with the organisational properties associated with resilience and robustness. For each step and each property, it has been evaluated whether the maintenance process can contribute to strengthen the property. As far as possible, concrete examples/suggestions have been provided.

In the following three subsections, some examples from Table 3 and 4 are brought out and briefly presented.

6.1. Between maintenance and production

The maintenance unit can pursue improvements in the following: (1) proactivity to risk management in maintainable production systems, (2) decisiveness in discouraging risky imbalances between maintenance and production, (3) a learning culture that promotes safety in maintenance of hazardous production systems, (4) communication and coordination between maintenance and production staff in the maintenance work process of safety-critical production systems, (5) simplicity in maintenance planning, procedures and organisation in relation to safety-critical production systems (Okoh and Haugen, 2014b), (6) looseness of couplings in maintenance organisation to tolerate shortcomings in production organisation, (7) organisational and technical redundancy for safety-critical production systems, (8) management of change related to alterations in the maintenance-production network, and (9) emergency preparedness and response to accidental events arising from maintenance-production interactions. Some of these and more examples are presented in Tables 3 and 4.

Table 2: Robustness and resilience properties

Properties	**Meanings**	**Perspectives**
Proactivity	Foreseeing what can go wrong and deploying barriers in advance.	Energy-barrier, HRO and resilience engineering
Redundancy	Deploying more than one means to a required function.	Energy-barrier and HRO
Simplicity	Making the design of organisational interactions simple.	Normal accident
Loose couplings	Allowing slacks, variant sequences, alternative means and independent events in organisations.	Normal accident
Learning	Reviewing incidents and nearmisses, sharing/updating situation or industry knowledge.	HRO and resilience engineering
Decisiveness	Successfully balancing goals, e.g. production-safety goals.	Conflicting objectives, adaptation and drift
Communication and coordination	Exchanging information and acting on it harmoniously.	Man-made disaster
Emergency response	The quality to readily intervene in accidental events.	Resilience engineering
Management of change	Management of organisational-related, operational and environmental changes.	Resilience engineering

6.2. Between maintenance and support

The maintenance unit can pursue improvements in the following: (1) proactivity to management of obsolescence of critical parts, (2) decisiveness in confirming the responsible party for critical part replacement between maintenance and external technical support, (3) learning on critical part verification, (4) communication and coordination for technical support via server-based maintenance management systems, (5) simplicity of maintenance support systems, e.g. maintenance-related cyber-physical systems, (6) looseness of couplings in relation to fault tolerance of e.g. computerized maintenance management systems, (7) organisational redundancy in relation to suppliers of critical parts, (8) management of change with respect to alterations in the maintenance-support network, and (9) emergency preparedness in conjunction with the dedicated emergency response department. These feature more prominently in the planning/scheduling/failure diagnosis phase of the maintenance work process as shown in Table 3.

However, in the other phases of the maintenance work process, one tends to see more of the adaptability of maintenance to support, through the application by the maintenance unit, of the management of change (MOC) procedure related to both. This is also shown in Table 3 and Table 4.

6.3. Between maintenance and the environment

The maintenance unit can pursue improvements in the following: (1) proactivity to management of unsafe environmental conditions arising during maintenance, e.g. through maintenance optimization in relation to dynamic grouping of maintenance activities (Wildeman et al., 1997), (2) decisiveness in adapting maintenance operations to the livelihood of the host community, e.g. through diligent waste management and site reinstatement efforts (3) learning on keeping a conducive working environment, (4) communication and coordination on weather forecast and cultural issues related to the host community, (5) simplicity in maintenance operations in relation to concurrent activities in neighbouring areas, (6) looseness of couplings with respect to decentralizing maintenance for speedy response to hazardous effects from environmental forces, (7) management of change (MOC) procedure relevant to maintenance-related environmental changes, and (8) emergency maintenance to prevent or mitigate the effects of sudden environmental hazards. Some of these and more examples are presented in Tables 3 and 4.

Table 3: Maintenance contribution to organisational robustness

Maintenance-related work process	Links	Proactivity	Decisiveness	Learning	Communication and coordination	Simplicity	Loose couplings	Redundancy	Management of change (MOC)	Emergency response
Planning / Scheduling / Failure diagnosis	Between maintenance and production	Joint Job Safety Analysis (JSA) or toolbox meetings prior to inter-departmental related work.	Advising on a joint site visit to avoid discrepancies. Joint agreement on guidelines for potential trade-offs that will not create imbalance between business and safety objectives	Joint planning of HSE review meetings, participation in HSE workshops and other related forums	Cooperation on PTW, CMMS, HAZID, safety planning and maintenance / production interface lead	Simplification of production-maintenance interfaces and elimination of bureaucracies in the network between production-maintenance.	Putting joint alternative operational plans in place and being tolerant of delays, errors and failures in mutual interaction	Joint agreement on training and keeping standby personnel who are multi-skilled in both production and maintenance regardless of any existing outsourcing policy	Collaboration on any required reorganisation process related to operational staff. Joint development of MOC procedure relevant to maintenance-production relations	Joint emergency exercises/drills planning, emergency maintenance planning for deficient safety critical equipment, etc.
	Between maintenance and support	Anticipating the obsolescence of critical items and hence doing timely upgrade	Decisiveness on whom between the user and manufacturer is responsible for deciding on and confirming parts replacement	Training of maintenance staff for the ability to verify critical parts before and after supply.	Cooperation on availability of critical maintenance related resources and on e-PTW and CMMS software support.	Agreeing on re-design for dependability improvement.	Decentralizing the supply of critical resources related to maintenance and allowing some delay in delivery.	Keeping redundant suppliers of critical maintenance related resources on vendors list.	Development of MOC procedure relevant to maintenance-support relations	Joint emergency exercises/drills planning, emergency maintenance planning for deficient emergency response equipment, etc.
	Between maintenance and the environment	Optimizing maintenance to mitigate the effects of adverse environmental conditions	Adaptability of maintenance to installations' host communities	Training of maintenance staff for contingency management	Maintenance of communication channels with the environment and exchange of information.	Reduce complexity in maintenance in relation to concurrent activities in neighboring sites	Decentralizing maintenance for speedy response to effects from external forces so as to mitigate losses		Development of MOC procedure relevant to maintenance-related environmental changes.	Emergency maintenance planning to prevent or mitigate the effects of unsafe environmental conditions.
Mobilization / Shutdown	Between maintenance and production	Pre-mobilization inspection and awareness on likelihood of residual process chemicals	Joint agreement on partial or total shutdown	Ensure real-time supervision for hazardous on-the-job training	Cooperation on hazard control at shutdown. Use of PTW, HAZID, checklist etc.			If bypassing redundant safety systems, apply suitable safety alternative	Applying changes specified by MOC procedure	Agreeing on shutting down to limit state of emergency etc.
	Between maintenance and support								Applying changes specified by MOC procedure	
	Between maintenance and the environment	Warning third parties off hazardous activities and work areas			Cooperation with host community by paying attention to culture-sensitive issues being raised				Applying changes specified by MOC procedure	Performing emergency maintenance to prevent or mitigate the effects of unsafe environmental conditions
Preparation for maintenance work	Between maintenance and production	Identifying and securing isolation points, and evacuation of hazardous materials	Joint agreement on optimal isolation and advising against unmanning of control rooms	Ensure real-time supervision for hazardous on-the-job training	Cooperation on use of PTW, checklists, HAZID tools etc.			If bypassing redundant safety system, apply suitable safety alternative.	Applying changes specified by MOC procedure	
	Between maintenance and support								Applying changes specified by MOC procedure	Joint emergency exercise/drill execution
	Between maintenance and the environment	Warning third parties off hazardous activities and work areas			Cooperation with host community by paying attention to culture-sensitive issues being raised				Applying changes specified by MOC procedure	Performing emergency maintenance to prevent or mitigate the effects of unsafe environmental conditions

Table 4: Maintenance contribution to organisational robustness

Maintenance-related work process	Links	Proactivity	Decisiveness	Learning	Communication and coordination	Simplicity	Loose couplings	Redundancy	Management of change (MOC)	Emergency response
Performance of the maintenance work	Between maintenance and production	Use of Job Hazard Analysis	Joint agreement on substituting a part with a non-original one	Ensure real-time supervision for hazardous on-the-job training	Cooperation on hazard control during the maintenance phase. Use of PTW, checklists, HAZID etc. Reject unmanning of control rooms			If bypassing redundant safety systems, apply suitable safety alternative.	Applying changes specified by MOC procedure	
	Between maintenance and support								Applying MOC procedure	
	Between maintenance and the environment	Warning third parties off hazardous activities and work areas			Cooperation with host community by paying attention to culture-sensitive issues being raised				Applying changes specified by MOC procedure	Performing emergency maintenance to prevent or mitigate the effects of unsafe environmental conditions
Startup	Between maintenance and production	Doing Pre-Startup Safety Review (PSSR)	Joint agreement on optimal deisolation. Advising against unmanning of control rooms.	Ensure real-time supervision for hazardous on-the-job training	Cooperation on use of PTW, HAZID, checklists etc.			If bypassing redundant safety systems, apply suitable safety alternative.	Applying changes specified by MOC procedure	
	Between maintenance and support								Applying changes specified by MOC procedure	
	Between maintenance and the environment	Warning third parties off hazardous activities and work areas			Cooperation with host community by paying attention to culture-sensitive issues being raised				Applying changes specified by MOC procedure	Performing emergency maintenance to prevent or mitigate the effects of unsafe environmental conditions
Normal Operation	Between maintenance and production	Use of Job Hazard Analysis	Joint agreement on on-line maintenance procedure. Advising against unmanning of control rooms	Ensure real-time supervision for hazardous on-the-job training	Cooperation on use of PTW, HAZID, checklist etc.			If bypassing redundant safety systems, apply suitable safety alternative.	Applying changes specified by MOC procedure	
	Between maintenance and support								Applying changes specified by MOC procedure	
	Between maintenance and the environment	Warning third parties off hazardous activities and work areas			Cooperation with host community by paying attention to culture-sensitive issues being raised				Applying changes specified by MOC procedure	Performing emergency maintenance to prevent or mitigate the effects of unsafe environmental conditions

The contents of Tables 3 and 4 represent some recommended best practices that will serve as opportunities for maintenance to contribute to the robustness of the process industry organisation. Some of the recommendations are peculiar to a given phase of the maintenance work process, whereas others necessarily cut across some phases.

7. Conclusion

This paper is one among several intended to give more insight into how to make the best out of maintenance in the process industries. The direction in this paper has been focused on what robustness and resilience properties exist in maintenance and how these can be improved in relation to maintenance interaction with other areas such as production and support and in turn improve the robustness and resilience of the process industries organisation. Over time, maintenance has been a proven contributor to the robustness of the physical systems in the industries, but whether maintenance can also contribute to the robustness and resilience of the organisation had yet to be investigated. Hence, the hypothesis that maintenance can also improve organisational properties that influence the ability to resist or counteract accidental events as well as the ability to adapt and recover from such events had to be investigated. This would enable us to see whether there is a possibility of developing new knowledge for the exploitation of additional maintenance values.

The fact that robustness can be seen as the ability to resist or counteract accidental events motivated the use of the various perspectives of organisational accidents (i.e. energy-barrier model, normal accident theory (NAT), high reliability organisations (HRO), man-made disaster (MMD) theory, conflicting objectives, adaptation and drift (COAD) theory and resilience engineering theory) as bases for the investigation. Besides, some of these perspectives have explained that accidents are not caused only by technical failures of physical systems, but in some cases by human and organisational factors or a combination of these.

The contribution of maintenance to organisational robustness and resilience, based on the improvement of the robustness and resilience properties of maintenance, were derived by mapping robustness and resilience properties (based on the accident perspectives) to the maintenance work process (i.e. Planning/scheduling/failure diagnosis, mobilization and shutdown, preparation for maintenance work, performance of the maintenance work, startup and normal operation) and the links between maintenance and production, maintenance and support, and maintenance and the environment. A given industry was considered as a triplet organisation consisting of the maintenance unit, the production unit and the support unit all in contact with the environment.

It has been shown in this paper how maintenance can improve robustness and resilience in organisations. The operational links between maintenance and each of the other elements (i.e. production, support and the environment) possess the potential for additional robustness and resilience to the organisation. The links represent means by which maintenance can interact in harmony with other units for the purpose of improving organisational robustness and resilience. As supported by (Rescher, 2005), such harmonious relationships at the elemental level will contribute to realizing the organisation's goal. Recommendations to the maintenance management of process industries for strengthening these links in order to achieve added robustness and resilience have also been proposed.

References

Agarwal, J., Blockley, D. I., Woodman, N. J., 2007. Vulnerability of Systems. Civil Engineering and Environmental Systems 18, 141–165.

Anderies, J. M., Janssen, M. A., Ostrom, E., 2004. A Framework to Analyze the Robustness of Social-ecological Systems from an Institutional Perspective. Ecology and Society 9 (1).

Asbjø rnslett, B., Rausand, M., 1999. Assess the vulnerability of your production system. Production Planning and Control 10 (3), 219–229.

BBC, 2011. Germany: Nuclear power plants to close by 2022.
URL `http://www.bbc.co.uk/news/world-europe-13592208`

Boissieres, I., Marsden, E., 2005. Organisational Factors of Robustness. In: Proceedings of the 2nd International ISCRAM Conference. Brussels, pp. 117–122.

Chandra, C., Grabis, J., 2007. Supply Chain Configuration: Concepts, Solutions, and Applications, 1st Edition. Springer, New York.

CSB, 2007. Investigation Report, Refinery Explosion and Fire, (15 Killed, 180 Injured), BP, Texas City, Texas, March 23, 2005. Report No. 2005-04-I-TX. Tech. rep., U.S. Chemical Safety Board, Texas.

Cullen, L., 1990. The Public Inquiry into the Piper Alpha Disaster, Vols. 1 and 2 (Report to Parliament by the Secretary of State for Energy by Command of Her Majesty, November 1990). Tech. rep., Her Majesty's Government, London.

Dekker, S., 2006. Resilience Engineering: Chronicling the Emergence of Confused Consensus. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 7, pp. 77–92.

Dekker, S., Hollnagel, E., Woods, D. D., Cook, R., 2008. Resilience Engineering : New directions for measuring and maintaining safety in complex systems. Tech. Rep. November, Lund University School of Aviation.

Duffuaa, S. O., 1995. Maintenance and quality : the missing link. Journal of Quality in Maintenance Engineering 1 (1), 20–26.

EN 13306, 2010. Maintenance: Maintenance Terminology. Tech. rep., European Committee for Standardization, Brussels.

Ferdows, K., 1997. Making The Most of Foreign Factories. Harvard Business Review, 73–88.

Foster, H. D., 1993. Resilience theory and system evaluation. In: Wise, J. A.; Hopkin, V. D.; Stager, P. (Ed.), Verification and Validation of Complex Systems: Human Factors Issues. Springer, Berlin, pp. 35–60.

Galliot, B., Chera, S., 2010. The Hydra model: disclosing an apoptosis-driven generator of Wnt-based regeneration. Trends in cell biology 20 (9), 514–23.

Gell-Mann, M., 1994. The Quark and the Jaguar: Adventures in the Simple and the Complex. W.H. Freeman and Company, New York.

Gibson, J. J., 1961. The contribution of experimental psychology to the formulation of the problem of safety–a brief for basic research. Behavioral approaches to accident research, 77–89.

Grote, G., 2011. Reviews for Resilience Engineering in Practice. In: Hollnagel, E., Paries, J., Woods, D. D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate, Surrey.

Hale, A., Heijer, T., 2006. Defining Resilience. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 3, pp. 35–40.

Hollnagel, E., 2009. Safety Culture, Safety Management, and Resilience Engineering. Tech. rep., MINES ParisTech, Paris.
URL `http://www.atec.or.jp/Forum\_\_09\_\_Hollnagel.pdf`

Hollnagel, E., 2011. Prologue: The Scope of Resilience Engineering. In: Hollnagel, E., Paries, J., Woods, D. D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate, Surrey.

Hollnagel, E., Sundström, G., 2006. States of Resilience. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 21, pp. 339–346.

Homlong, E., 2010. Reliability, Availability, Maintainability and Supportability factors in an Arctic offshore operating environment: Issues and challenges. Ph.D. thesis, Stavanger.

Hopkins, A., 1999. The limits of normal accident theory. Safety Science 32, 93–102.

ISO, 2009. ISO Guide 73:2009 - Risk management – Vocabulary. International Organization for Standardization, Geneva.

JCCP, 2009a. Customized Program in Japan on "Maintenance & Safety Management" for Saudi Aramco. Tech. rep., Japan Cooperation Center, Petroleum, Tokyo.

JCCP, 2009b. Seminar on "Refinery Maintenance Management and TPM" Held at Saudi Aramco's Ras Tanura Refinery. Tech. rep., Japan Cooperation Center, Petroleum, Tokyo.

JCCP, 2012. CPO Seminar on Total Productive Maintenance Management (TPM) Held Jointly with Saudi Aramco. Tech. rep., Japan Cooperation Center, Petroleum, Tokyo.
URL `http://www.jccp.or.jp/english/wp-content/uploads/cpo\_tpm\_saudi-aramco.pdf`

Jen, E., 2005. Stable or Robust? What's the Difference? In: Jen, E. (Ed.), Robust Design: A Repertoire of Biological, Ecological and Engineering Case Studies. Oxford University Press, Oxford, Ch. 1, p. 7.

Jonsson, P., 1997. The status of maintenance management in Swedish manufacturing firms. Journal of Quality in Maintenance Engineering 3 (4), 233–258.

LaPorte, T., Consolini, P., 1991. Working in Practice but Not in Theory: Theoretical Challenges of High-Reliability Organizations. Public Administration Research and Theory 1 (1), 19–47.

Leveson, N., Dulac, N., Zipkin, D., Cutcher-Gershenfeld, J., Carroll, J., Barrett, B., 2006. Engineering Resilience into Safety-Critical Systems. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 8, pp. 95–123.

McDonald, N., 2006. Organisational Resilience and Industrial Risk. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 11, pp. 155–180.

Nielsen, L., Holmefjord, A., 2004. How to Design a Robust Emergency Preparedness Organisation for Offshore Drilling. In: The Seventh SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production. Society of Petroleum Engineers, Calgary, pp. 1–4.

NS5814, 2008. NS 5814: Requirements for Risk Assessment, norwegian Edition. Standard Norge, Oslo.

Ø ien, K., Schjø lberg, P., Meland, O., Leto, S., Spilde, H., 2010. Correct Maintenance Prevents Major Accidents. MaintWorld, 26–28.

Okoh, P., 2010. Maintenance Concept Database Solution (MCDS). Master thesis, Norwegian University of Science and Technology (NTNU) Trondheim.
URL `http://ntnu.diva-portal.org/smash/record.jsf?pid=diva2:427941`

Okoh, P., Haugen, S., 2012. The Effect of Maintenance Seen From Different Perspectives on Major Accident Risk. In: IEEE International Conference on Industrial Engineering and Engineering Management. IEEEXplore, Hong Kong, pp. 917–921.

Okoh, P., Haugen, S., 2013a. Maintenance-related major accidents: Classification of causes and case study. Loss Prevention in the Process Industries 26, 1060–1070.

Okoh, P., Haugen, S., 2013b. The Influence of Maintenance on Some Selected Major Accidents. Chemical Engineering Transactions 31, 493–498, DOI: 10.3303/CET1331083.

Okoh, P., Haugen, S., 2014a. A study of maintenance-related major accident cases in the 21st century. Process Safety and Environmental Protection-DOI: 10.1016/j.psep.2014.03.001.

Okoh, P., Haugen, S., 2014b. Application of Inherent Safety to Maintenance-related Major Accident Prevention on Offshore Installations. Chemical Engineering Transactions 36, 175–180, DOI: 10.3303/CET1436030.

Okoh, P., Haugen, S., 2014c. The implication of maintenance in major accident causation. Loss Prevention Bulletin (236), 11–14.

ORIOH, 2001. Risk Assessment and Management of Cold Related Hazards In Arctic Workplaces: Network of scientific institutes improving practical working activities. Tech. rep., Oulu Regional Institute of Occupational Health (ORIOH), Oulu.

Paries, J., 2011. Resilience and the Ability to Respond. In: Hollnagel, E., Paris, J., Woods, D. D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate, Surrey, Ch. 1, pp. 1–8, 9–27.

Pavard, B., Dugdale, J., Saoud, N. B.-b., Darcy, S., Salembier, P., 2007. Design of robust socio-technical systems.

Perrow, C., 1984. Normal Accidents: Living with High-Risk Technologies. Princeton University Press, New Jersey.

Pitblado, R., 2011. Global process industry initiatives to reduce major accident hazards. Journal of Loss Prevention in the Process Industries 24 (1), 57–62.

PSA, 2010. Management Regulations. Tech. rep., Petroleum Safety Authority, Stavanger, Norway.

Rasmussen, J., 1997. Risk Management in A Dynamic Society: A Modelling Problem. Safety Science 27 (2/3), 183–213.

Reason, J., 1997. Managing the risks of organisational accidents. Ashgate, Aldershot, UK.

Rescher, N., 2005. Cognitive harmony: the role of systemic harmony in the constitution of knowledge. University of Pittsburgh Press, Pittsburg.
URL `http://digital.library.pitt.edu/cgi-bin/t/text/text-idx?idno=31735062136340;view=toc;c=pittpress`

Rosness, R., Grø tan, T., Guttormsen, G., Herrera, I., Steiro, T., Stø rseth, F., Tinmannsvik, R., Wæ rø, I., 2010. Organisational accidents and resilient organisations: Six perspectives, revision 2 Edition. SINTEF Industrial Management, Trondheim.

Sagan, S. D., 1993. The Limits of Safety: Organizations, Accidents, And Nuclear Weapons. Princeton University Press, New Jersey.

Saleh, J., Marais, K., Cowlagi, R., 2010. Highlights from the literature on accident causation and system safety: Review of major ideas, recent contributions, and challenges. Reliability Engineering & System Safety 95, 1105–1116.

SINTEF, 2011. The Deepwater Horizon accident: Causes, lessons learned and recommendations for the Norwegian petroleum activity. Tech. rep., SINTEF Society and Technology, Trondheim.

Swanson, L., 1997. An empirical study of the relationship between production technology and maintenance management. International Journal of Production Economics 53, 191–207.

Turner, B. A., 1978. Man-Made Disasters. Wykeham Science Series, London.

Wallace, S., Merritt, C., 2003. Know when to say 'when': A review of safety incidents involving maintenance issues. Process Safety Progress 22 (4), 212–219.

Wildeman, R. E., Dekker, S., Smit, A., 1997. A dynamic policy for grouping maintenance activities. European Journal of Operational Research 99 (3), 530–551.

Wilson, A., 2002. Asset Maintenance Management: A Guide to Developing Strategy and Improving Performance, 1st Edition. Industrial Press Inc., New York.

Woods, D. D., 2006a. Essential Characteristics of Resilience. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 2, pp. 21–34.

Woods, D. D., 2006b. Resilience engineering: Redefining the culture of safety and risk management. Human Factors and Ergonomics Society Bulletin 49 (12), 1–3.

Woods, D. D., 2011. Resilience and the Ability to Anticipate. In: Hollnagel, E., Paries, J., Woods, D. D., Wreathall, J. (Eds.), Resilience Engineering in Practice: A Guidebook. Ashgate, Surrey, Ch. 9, pp. 121–125.

Wreathall, J., 2006. Properties of Resilient Organisations: An Initial View. In: Hollnagel, E., Woods, D. D., Leveson, N. (Eds.), Resilience Engineering: Concepts and Precepts. Ashgate, Surrey, Ch. 17, pp. 275–285.