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# Transportation Systems

## Managing Performance through Advanced Maintenance Engineering

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# Chapter 12
# Assessing the Potential for Resilient Performance in Rolling Stock Maintenance: The Pitstop Case

**Jan-Jaap Moerman, A. J. J. Braaksma and Leo A. M. van Dongen**

**Abstract** Unexpected failures of physical assets are a primary operational risk to asset-intensive organisations. Managing these unexpected failures is essential for reliable performance. The main railway operator in the Netherlands expects more unexpected failures as a result of the introduction of new rolling stock in an already highly utilised railway system. One of the challenges of maintenance management is to determine if the current corrective maintenance system has the capabilities to cope with an increase of unexpected defects of rolling stock in the upcoming years or that further improvements are required. In the last decade, Resilience Engineering has emerged as a new paradigm in a number of high-risk sectors to detect and respond to unexpected events effectively. Attempts to apply this concept outside these sectors have so far been limited. The main purpose of this study is to explore the applicability of Resilience Engineering in the field of rolling stock maintenance by assessing the potential for resilient performance using an in-depth case study. A comparison between the characteristics of corrective maintenance and emergency healthcare showed that the studied contexts are highly comparable which suggests that the concept of Resilience Engineering may also apply to corrective maintenance of rolling stock. This study contributes to theory by replicating and adapting Resilience Engineering for corrective maintenance of rolling stock and provides maintenance practitioners guidance on how to measure current resilience and identify improvement areas.

**Keywords** Resilience engineering · Rolling stock · Corrective maintenance

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## 12.1 Introduction

Public transport relies on the proper functioning of physical assets. Unexpected failures of physical assets are a considerable operational risk to asset-intensive organisations (LaRiviere et al. 2016). Managing these unexpected failures is essential for reliable performance. In the railway industry, organisations must carefully manage potentially hazardous technical systems which, if mismanaged, could lead to catastrophic failures. Passenger railway organisations, like the Nederlandse Spoorwegen (NS), face an increasingly complex environment due to new digital technologies, higher utilisation of the railway network and strong political influences. This will, most likely, increase the number of unexpected failures of rolling stock in the near future. One of the key challenges of maintenance management is to determine if the current corrective maintenance system has the capabilities to cope with an expected increase of unexpected defects of rolling stock in the upcoming years or that further improvements are necessary.

In the last decade, resilience has emerged as a new paradigm in a number of high-risk sectors to increase safety and reliability. Typical examples of resilience can be found in healthcare (Fairbanks et al. 2014) and financial systems (Sundstrom and Hollnagel 2011). It is resilience that gives these systems the ability to perform successfully despite severe conditions that easily could lead to failure. It is also resilience that allows them to recover quickly after a failure. For example, work within the Emergency Department (ED) in emergency healthcare is difficult because the system is inherently limited to reacting to events. Work takes place between the orderly world of the hospital and the unpredictable world outside it. Nevertheless, clinicians find ways to manage conflicts among the need to provide emergency care and to economise on resources at the same time. For instance, they dedicate beds to improve efficiency and they identify outside hospitals and clinics to increase capacity (Wears et al. 2008).

Resilience Engineering (RE) is a paradigm that emerged from the field of safety management. RE aims to improve the ability of a complex socio-technical system to adapt to disturbances, disruptions and changes (Hollnagel and Woods 2006). In emergency healthcare, RE studies try to make ambulatory care a designed (resilient) system in order to prevent current practices of a patchwork of temporary fixes. The reason behind this idea is that better designs will improve care continuity, supporting clinicians in their care for patients (Nemeth et al. 2011). Table 12.1 shows the characteristics of emergency healthcare and corrective maintenance illustrating the similarities in context despite the different type of assets. Corrective maintenance refers to all activities performed to repair a failure or a malfunctioning component or system. A glance at this table shows that, despite differences in the nature of the work and risks involved, the concept of resilience, as studied in healthcare, might also be applicable in corrective maintenance of physical assets.

The main purpose of this study is to explore the applicability of RE in the field of rolling stock maintenance by assessing the potential for resilient performance using an in-depth case study at a large passenger railway operator in the Netherlands

**Table 12.1** Characteristics of emergency healthcare, partly based on Nemeth et al. (2011), and corrective maintenance partly based on Dhillon (2002), illustrating similarities in context

| Characteristics | Emergency healthcare | Corrective maintenance |
|---|---|---|
| Type of asset | Human assets | Physical assets |
| Predictability | Low, unexpected care for patients | Low, unexpected defects of physical assets |
| Resources | Limited, economise on resources | Limited, economise on resources |
| Level of expertise | High, limited availability (physicians) | Medium, limited availability (technicians) |
| Type of system | Socio-technical | Socio-technical |
| Level of risk | High risks | Low/medium risks |
| Pace of events | No control, unscheduled | No control, unscheduled |

using the Resilience Analysis Grid (Hollnagel 2011). One of the primary concerns to the evolution of resilience as a theory is the academical and practical use of the concept of resilience at the organisational level (Righi et al. 2015). This study contributes to the range of the RE theory by replicating an existing theory in a new field. Although resilience in rolling stock maintenance is still in its infancy, other research in railway operations already shows the value of applying RE concepts (e.g. Siegel and Schraagen 2017). Furthermore, this study aims to provide guidance to practitioners on how to assess and improve their potential for resilient performance in managing unexpected failures of their physical assets.

The remainder of this chapter is structured as follows. Section 12.2 introduces the key concepts of resilience followed by the research approach in Sect. 12.3. Section 12.4 introduces the case study in maintenance at a large passenger railway operator in the Netherlands. Section 12.5 presents the results of the case study followed by a discussion and conclusion on resilience in the context of corrective maintenance.

## 12.2 Literature Background

This section presents the concepts of corrective maintenance, resilience and resilience engineering. It starts by introducing corrective maintenance as a socio-technical system.

### 12.2.1 Maintenance as a Socio-Technical System

Maintenance is essential in the entire life of physical assets. Maintenance activities are essential to ensure that systems can fulfil their intended function (Gits 1992). For a long time, maintenance was not considered to be a problem requiring much attention (Van Dongen 2015). With the increasing complexity of technical systems, higher utilisation rate of installations, and the safety and sustainability of physical assets, maintenance gained more and more attention.

Three basic types of maintenance can be distinguished: Use-based maintenance, condition-based maintenance and failure-based maintenance (Gits 1992). Use-based maintenance prescribes maintenance after a specific period of use. It is based on a statistical model of forecasting failures. Condition-based maintenance prescribes maintenance based on the condition. It is based on a deterministic model of predicting failures. This type of maintenance uses inspection and monitoring. Both use-based maintenance as well as condition-based maintenance can result in preventive- and corrective maintenance. Nevertheless, unexpected failures may still occur. Failure-based maintenance is aimed at prescribing repairs in case of failures and results in corrective maintenance only. The scope of the Maintenance Pitstop System, which will be further introduced in the case study section, is on corrective maintenance only.

The maintenance of physical assets, such as the maintenance of rolling stock, can also be considered as a socio-technical system. Socio-technical systems involve complex interactions between humans (e.g. mechanics, engineers, production managers), machines (e.g. maintenance equipment, rolling stock, spare parts) and the environment of the work system (Trist 1981). An increase in complexity has made systems intractable, hence underspecified (Hollnagel 2012). Systems perform because humans are able to learn to overcome or compensate shortcomings in design and because they can adapt or adjust their performance to the demands (Hollnagel 2012). However, to remain reliable for a socio-technical system, it must be able to handle unexpected situations in such a way that the performance is still within its boundaries (Weick 1987). This requires not only standardised operating procedures but also resilience (Righi et al. 2015).

### 12.2.2 Resilience and Resilience Engineering

In the past decade, the concept of 'resilience' turned up in several academic fields as also identified by Nemeth and Herrera (2015). For example, in management literature resilience can refer to the ability of a firm to withstand difficult economic conditions (Sutcliffe and Vogus 2003). Political science considers resilience as the ability of groups and communities to withstand unforeseen challenges, such as hurricanes and tsunamis (Birkland and Waterman 2009). In civil engineering, resilience is strongly related to the ability of buildings, structures and infrastructures to cope with (environmental) challenges such as earthquakes (Bruneau et al. 2003). As the concept of 'resilience' has been recognised in a number of fields, it has resulted in many definitions. One of the early definitions is from Wildavsky (1989). He defines resilience as: "The capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back". Hollnagel and Woods (2006) defines resilience 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 even after a major mishap or in the presence of continuous stress".

Resilience Engineering (RE) emerged from safety management and its main focus is the balance between productivity and safety in complex systems. It aims to provide tools and guidance to manage risk, hereby acknowledging the inherent complexity of systems and the need for variability in performance. The assumption is that resilience can be engineered into a complex socio-technical system in order to support the use of adaptive capacity (Patriarca et al. 2018) to enhance the ability to adapt or absorb disturbance, disruption and change (Hollnagel and Woods 2006). Fairbanks et al. (2014) define RE as: "The deliberate design and construction of systems that have the capacity for resilience".

The resemblance between RE and High Reliability Organizations (HRO) (La Porte 1996; Roberts 1990; Sutcliffe 2011; Sutcliffe and Vogus 2003; Weick et al. 2008), which are considered two similar schools of thought, is remarkable. As described by Pettersen and Schulman (2016), HRO research shows that high reliability is associated with the management of variability in terms of mindfulness, trust, sensemaking, communication and cooperation among members of an organisation in order to keep work within acceptable conditions to achieve high levels of reliability (Roe and Schulman 2008; Schöbel 2009; Schulman 1993). RE can be considered the action agenda of HRO (Hollnagel et al. 2007) and underlines several HRO characteristics as identified by Dekker and Woods (2010) in their analysis on ensuring resilience in HROs. This study adopts the RE perspective to assess the resilience of the system.

Corrective maintenance refers to all activities performed to repair a failure or a malfunctioning component or system. Activities are prioritised depending on their level of severity. Having a sufficient level of corrective maintenance helps to reduce the magnitude of the impact and the time to recover from failures. In this sense, corrective maintenance can already be considered as a policy for resilience (Labaka et al. 2015). However, how can management determine which abilities need to be further developed to increase resilient performance?

### *12.2.3 Assessment of the Four Abilities of Resilience Engineering*

Resilience refers to something a system does (a capability or a process) rather than to something the system has (a product). Therefore, resilience cannot be measured by counting specific outcomes such as accidents or incidents. However, in response to

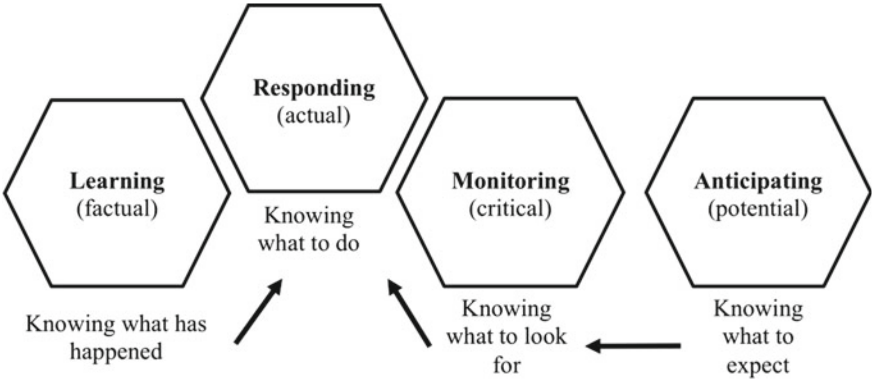


**Fig. 12.1** Four cornerstones of Resilience Engineering (RE). Adopted from Hollnagel (2011)

the need for measuring resilience (Wreathall 2009), Hollnagel (2011) introduced an approach to measure the resilience of a system. His approach focuses on four abilities that together constitute resilience: The ability to respond, the ability to monitor, the ability to anticipate and the ability to learn. These abilities are respectively linked to the actual, the critical, the potential and the factual as illustrated in Fig. 12.1. The four abilities need to be addressed by any organisation to some extent in order to be resilient. A typical example is the fire brigade. For the fire brigade, it is more important to be able to respond to actual fire incidents (ability to respond) than to consider potential fire incidents (ability to anticipate) as no fire incident is the same (Hollnagel 2010). Nevertheless, in order to respond adequately, monitoring and learning are also essential.

- Learn from the past (ability to learn) is defined as: "Knowing what has happened, or being able to learn from experience, in particular, to learn the right lessons from the right experience" (Hollnagel 2011);
- Respond to actuals (ability to respond) is defined as: "Knowing what to do, or being able to respond to regular and irregular changes, disturbances and opportunities by activating prepared actions or by adjusting the current mode of functioning" (Hollnagel 2011);
- Monitor weak signals (ability to monitor) is defined as: "Knowing what to look for (leading indicators), or being able to monitor that which is or could seriously affect the system's performance in the near term, positively or negatively" (Hollnagel 2011);
- Anticipate the future (ability to anticipate) is defined as: "Knowing what to expect or being able to anticipate developments further into the future, such as potential disruptions, novel demands or constraints, new opportunities, or changing operating conditions" (Hollnagel 2011).

The four abilities of resilience appear significant in terms of describing how people deal successfully with unexpected and unforeseen events (Rankin et al. 2014) or to promote a more strategic and tactical control within daily operations (Praetorius and

Hollnagel 2014). The four abilities are related to each other. The ability to respond is dependent on the ability to monitor because otherwise, the system would always need to be in a state of high alert to respond. Learning can be a result of monitoring and may improve the response to actuals.

To determine the extent to which each ability is present in, or supported by, a system, one can use a so-called functional decomposition to reveal which specific functions or sub-functions are needed to enable a resilient system (Hollnagel 2011). This can be used to develop a profile of the current performance and improvement potential for each ability. Together the overall improvement potential for resilient performance can be identified. This has been called the Resilience Analysis Grid or RAG (Hollnagel 2011). The RAG provides a foundation for developing an assessment tool in assessing resilience at organisational, team and individual levels (van der Vorm et al. 2011). The RAG is not a widely diffused method, except for a few case studies (Patriarca et al. 2018). The RAG requires users to tailor it to the needs of the organisation being studied (Hollnagel 2011). To the knowledge of the authors, the RAG has so far never been used to assess resilience in corrective maintenance of rolling stock. The application of RE may offer new insights in managing unexpected failures of rolling stock.

## 12.3 Research Design

The primary purpose of this research is to explore the applicability of RE in rolling stock maintenance by assessing the improvement potential for resilience of a rolling stock maintenance system. This can be considered as an illustration of the theory (Wacker 1998) aimed at further elaboration to refine or extend an existing theory. The reluctance of Operations Management (OM) research to adopt ideas and methods from other subjects has been recognised as one of the weaknesses of OM research by Pilkington and Fitzgerald (2006). Some authors propose to borrow theories from adjacent areas to explain OM phenomena (Boer et al. 2015). For instance, Amundson (1998) gives examples of the potential utilisation in OM of theories from other fields, such as organisational learning, the resource-based view of the firm and transaction cost economics. This study can be considered a replication study based on the RAG method as introduced by Hollnagel (2010) in the domain of rolling stock maintenance using case study research. It adopted a single case study (Yin 2003), selecting three maintenance workshops of a large railway operator in the Netherlands which all implemented a Maintenance Pitstop System (MPS) for corrective maintenance.

The RAG assessment tool (Hollnagel 2010) was tailored to fit the context of rolling stock maintenance, in order to assess the resilience of the maintenance systems at three maintenance workshops in the Netherlands from an organisational level (Appendix) using semi-structured interviews and observations. All interviews were recorded and transcribed for coding and analysis and were validated by the respondents. Seeking confirmation from more data sources leads to more reliable results (Eisenhardt 1989). For a better understanding of the system, the MPS was observed using event observation forms at a randomly selected maintenance workshop. Additional documents and presentations were collected from the organisation for further analysis.

As the MPS concerned a 'standard' implementation based on the same concept, the analysis of the results was performed on an aggregated level including all three maintenance workshops. The ratings of the abilities, as shown in Appendix, are based on the coding of the transcriptions of the interviews, resulting in 189 quotations categorised by the four abilities of resilient performance. These quotations, together with the coded event observation forms, constituted an initial understanding of the abilities and were used to rate the items in each ability. These ratings were validated and discussed in a second round with participants to ensure the validity of the responses and interpretations, which resulted in several adjustments. Final results of the analysis were presented and discussed with senior management.

## 12.4 Corrective Maintenance in Rolling Stock—The Pitstop Case

The Nederlandse Spoorwegen (NS) is the primary railway operator in The Netherlands, having the exclusive right to operate passenger trains on the Dutch main railway network. The complexity of the railway system increases as a result of new (digital) technologies, higher utilisation of the railway network, strong political influences and the introduction of multiple series of new rolling stock. A higher complexity will most likely increase the number of unexpected failures of rolling stock in the near future. One of the challenges of maintenance management is to determine if the current corrective maintenance system can cope with an increase in unexpected failures.

### *12.4.1 Maintenance Pitstop System*

In 2015, in response to a lack of passenger seat capacity in operations, the NS introduced a Maintenance Pitstop System (MPS) to their maintenance workshops designed to effectively manage unexpected defects of rolling stock (corrective maintenance). The current ratio between preventive and corrective maintenance is approximately 50–50 (NS 2017). The primary objective of the NS was to decrease lead times of corrective maintenance on rolling stock to increase seat capacity in operations. The concept was partly based on the pitstop in Formula 1 motor racing, as a primary example of how a team can work together to effectively perform a limited number of complex tasks under time pressure with minimal error. The MPS resulted in a significant reduction of lead times in repairing rolling stock (NS 2017). To gain a thorough understanding of the MPS, the authors used rich picture modelling techniques, inspired by the Soft Systems Methodology (Checkland 2000). A rich picture illustrating the interaction between the various actors was constructed and discussed with key stakeholders of the MPS based on interviews and observations in the maintenance workshops (Fig. 12.2).

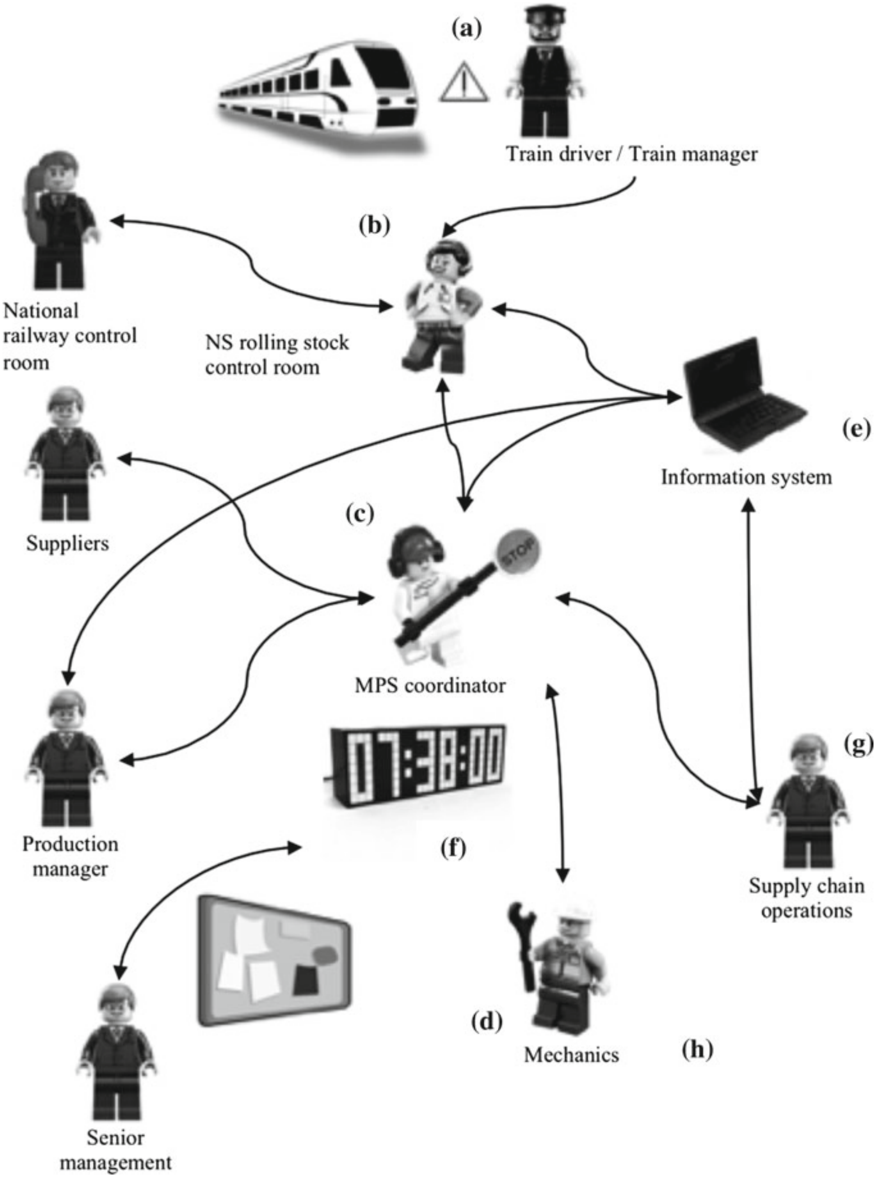


**Fig. 12.2** Rich picture of the Maintenance Pitstop System illustrating the interactions between the various actors

#### 12.4.1.1 Illustration of the Maintenance Pitstop System

As soon as a failure has been detected in operations (a), which disturbs safe and reliable train services, the train driver or the train manager (or the onboard train system) reports the failure to the NS rolling stock control room. The rolling stock control room (b) receives the defect notification, registers the Q-date in the Maximo system and assigns the priority. A Q-date is assigned to all defect trains to indicate the time a train is still available for service operations. This is called a defect in circulation (DIC). If a defect does not have a direct impact on train operations, it is repaired during the upcoming preventive maintenance cycle. If a failure needs to be repaired or replaced immediately, it will be shunted to a maintenance workshop for corrective maintenance. The Q-time enables control space to optimise train logistics and maintenance planning. Based on the priority classification, the national railway control room determines the best routing available based on the railway schedule of all train operators. Trains are routed towards service- or maintenance workshops, depending on the nature of the defect and the capabilities of the workshops.

The MPS team in a maintenance workshop consists of a MPS coordinator and three mechanics (d) with expertise in mechanical, electrical and electronic defects. MPS teams are assigned to a dedicated pitstop track. This guarantees the availability of (maintenance) resources to repair defects as soon as possible. The MPS coordinator (c) is physically located in one of the maintenance workshops and is responsible for coordinating all the maintenance activities. The MPS coordinator monitors the information system for defects (DIC) and determines which train set needs to be shunted to the maintenance workshop based on the Q-dates. The MPS coordinator schedules the train set using the Q-dates for optimal utilisation of the pitstop track.

The MPS coordinator retrieves information (for example failure data and an arrival date of the train set at the pitstop track) from the rolling stock control room or the information system (e) and publishes this information on the DIC board. The DIC board consists of three sections, showing defects in circulation, the current status of rolling stock on the pitstop track and an overview of repaired rolling stock (recidivism monitoring for two weeks). The MPS coordinator starts planning tasks and resources based on the available data. Examples of these tasks include contacting reliability engineers, system engineers and external suppliers for additional expertise in the diagnosis. The availability of spare parts is coordinated in close cooperation with supply chain operations.

When the train set arrives on the pitstop track, the MPS coordinator starts the clock (f), and the Pitstop form is moved from the defects in circulation section to the pitstop track section to start repairs. The clock counts down from 24 h to zero, indicating the time passed for repairing a specific train set. The clock is shown visually in the workshop, but also in the (head) offices and helps to create awareness of the current situation at the pitstop track.

The MPS team registers the train set on a second physical board, the Diagnostic board, and starts diagnosing and analysing. Based on this analysis a plan is made for repairing the failures, considering the available resources and capacity. The MPS team follows the Diagnostic board and registers their findings and solutions on the board. The MPS coordinator makes sure that the right equipment, knowledge and spare parts are available (g) and estimates the time for repair, which is useful for the rolling stock control room for the return of the train set in operations. A final test (A-control) will be performed before rolling stock will be declared ready for railway operations. As soon as the train set has been signed off in the system and is shunted off the pitstop track, the train set will be removed from the clock, the rolling stock control room is informed, and the train can be scheduled for operations. A train set which has been repaired, but returned within 14 days with the same failure, is called a recidivist and requires additional attention from the MPS team and other experts.

The MPS is operated 24-h a day by three shifts. After every shift, the two MPS teams discuss in detail the train sets which are in circulation (DIC) and which are currently at the pitstop track (h). For every train set, the Diagnostic board is used to explain the diagnosis and repairs already performed including the next steps. Based on this information the new MPS team start their maintenance activities. Three key performance indicators have been defined for the MPS: safety of maintenance operations, quality of repairs and the reliability of delivering rolling stock back to railway operations. The standard repair time for all maintenance workshops has been set at 16 h for a single train set.

### *12.4.2 Measuring the Potential for Resilient Performance*

An assessment of the four abilities of Resilience Engineering (RE) can provide insight into how to improve the MPS in dealing with an expected increase in unexpected failures. The RAG, as introduced in section two, offers the opportunity to develop indicators to assess system resilience qualitatively (Hollnagel 2011). Hollnagel (2011) states that it is difficult to provide an absolute rating of how well a system performs on all abilities. This is mainly because no standard can be used as a reference. Still, some kind of rating is necessary to gain insight into the potential for resilient performance. Hence, following Hollnagel (2011), the authors chose to use a Likert-type scale (Table 12.2) for the four abilities of resilience (see also Appendix).

**Table 12.2** Measurement scale of the abilities of resilience

| | |
|---|---|
| Excellent | The system meets and exceeds the criteria |
| Satisfactory | The system fully meets all reasonable criteria |
| Acceptable | The system meets the nominal criteria |
| Unacceptable | The system does not meet the nominal criteria |
| Deficient | There is insufficient ability to provide the required ability |
| Missing | There is no ability |

Adopted from Hollnagel (2011)

## 12.5 Case Results

The next subsections present the key findings of the assessment of the potential for resilient performance of the MPS. The results of the assessment are presented as radar charts based on the ratings as included in Appendix. The ratings are based on the overall assessment of the three maintenance workshops.

### 12.5.1 Ability to Respond to Failures

> Management is decisive, while we have all the knowledge. (MPS coordinator)

Respond to actuals is defined as: “Knowing what to do, or being able to respond to regular and irregular changes, disturbances and opportunities by activating prepared actions or by adjusting the current mode of functioning” (Hollnagel 2011). The radar chart (Fig. 12.3) gives a simple representation of the ability to respond, one of the four cornerstones of RE, as introduced in Sect. 12.2.3. The findings are related to the items (e.g. event list, relevance, duration) which constitutes the radar chart (Appendix).

The main findings, which contributed to a large extent to the ability to respond, was the strategic choice of a dedicated pitstop track and team 24-h a day (response capability) to ensure availability. The use of mobile teams for repairing unexpected failures (if technically feasible) also contributed to the resilience of the MPS and pre-

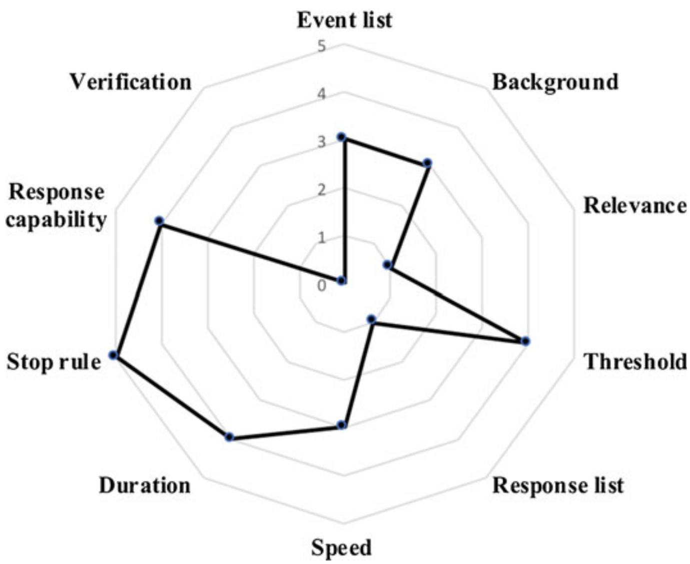


**Fig. 12.3** Radar chart of the results of the ability to respond (Hollnagel 2011), a.k.a. knowing what to do

vented unnecessary track movements of rolling stock. One of the concerns raised was the critical dependence on only a few experts in repairing specific failures (response capability). Another concern raised was the limited number of near-failures reported (event list). For example, train drivers, who manage to prevent unexpected failures successfully, do not report these near-failures. A third concern was the lack of a standard response list (relevance). If response lists are used, it is limited to local maintenance workshops and not shared between the different locations. The last concern was related to the under-specification of rolling stock which creates surprises and hinders the right diagnosis and repair of failures (duration).

### *12.5.2 Ability to Monitor Failures*

> Mechanics and other experts are ashamed to report failures and errors. (Team manager maintenance)

Monitoring weak signals is defined as: "Knowing what to look for, or being able to monitor what is or could seriously affect the system's performance in the near term – positively or negatively" (Hollnagel 2011). The radar chart (Fig. 12.4) gives a simple representation of the ability to monitor. The findings are related to the items (e.g. validity, relevance) which constitutes the radar chart (Appendix).

Results of the assessment indicated lower ratings for a number of items in the ability to monitor. One of the key strengths of the MPS was the countdown clock,

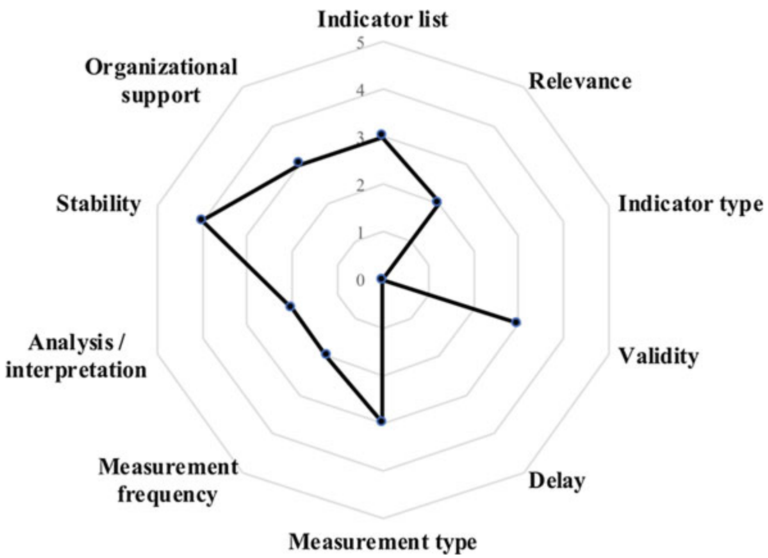


**Fig. 12.4** Radar chart of the results of the ability to monitor (Hollnagel 2011), a.k.a. knowing what to look for

which contributed to the awareness of mechanics, management and staff on what is happening in the pitstop and ensured a sense of urgency when a train is longer than 24 h on the pitstop track (indicator list). The pitstop clocks were also displayed at the central head office and available via mobile apps. The introduction of the recidivism section ensured pro-active monitoring of repaired train sets of maximum 14 days. Nevertheless, monitoring of repaired train sets was limited to the local maintenance workshop. One of the concerns was the limited use of automatic condition-based monitoring, i.e. lack of sensors and indicators on train sets to be able to detect unexpected failures, which prevents the use of leading and lagging indicators for accurate monitoring and detection of (near-)failures (indicator type).

### *12.5.3 Ability to Anticipate Future Failures*

> We need to get more in control on seasonal influences as they are very disturbing for the operational processes, historical data should be analysed. (Maintenance data analyst)

Anticipate the future is defined as: "Knowing what to expect or being able to anticipate developments further into the future, such as potential disruptions, novel demands or constraints, new opportunities, or changing operating conditions" (Hollnagel 2011). The radar chart (Fig. 12.5) gives a simple representation of the ratings within the ability to anticipate. The findings are related to the items (e.g. expertise, culture) which constitutes the radar chart (Appendix).

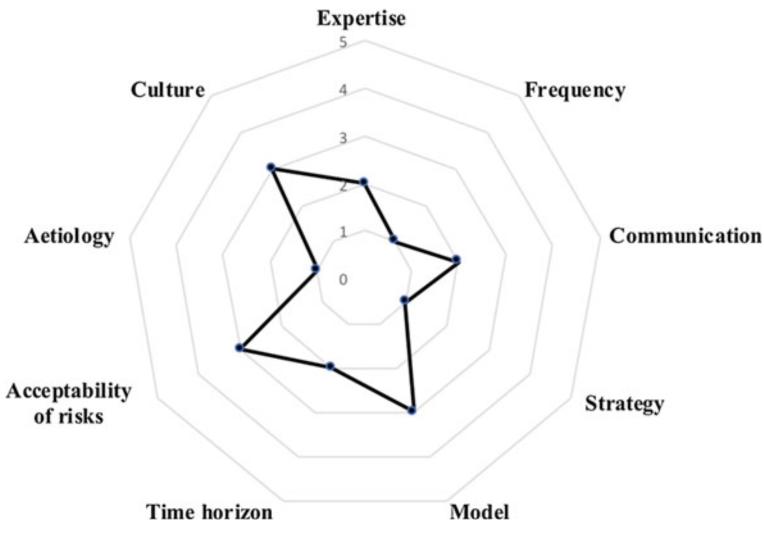


**Fig. 12.5** Radar chart of the results of the ability to anticipate (Hollnagel 2011), a.k.a. knowing what to expect

Results of the assessment indicated lower ratings for a number of items in the ability to anticipate. One of the findings was the lack of forecasting of unexpected failures based on seasonal influences (for example an increase in wear progress of railway wheels during autumn as a result of leaves on the track) and the condition of rolling stock (time horizon). The MPS coordinator pro-actively monitors the information system to identify train sets in operations with unexpected failures to be repaired (expertise). The structured approach to unexpected failures increased the level of control and the space to anticipate future events. Nevertheless, an explicit model of the future (strategy) was still difficult to imagine. Anticipation was mainly short-term and focussed on the local maintenance workshop.

### *12.5.4 Ability to Learn from Failures*

> We need to develop ourselves into a dynamic team. This only happens when we are confronted with high variability in the environment. (MPS coordinator)

Learn from the past is defined as: "Knowing what has happened, or being able to learn from experience, in particular, to learn the right lessons from the right experience" (Hollnagel 2011). The radar chart (Fig. 12.6) gives a simple representation of the ability to learn. The findings are related to the items (e.g. learning basis, formalisation) which constitutes the radar chart (Appendix).

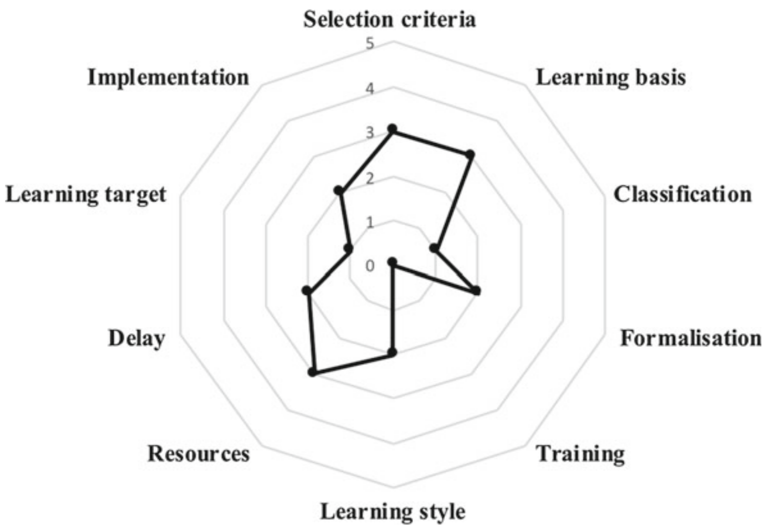


**Fig. 12.6** Radar chart of the results of the ability to learn (Hollnagel 2011), a.k.a. knowing what has happened

Results of the assessment indicated lower item scores on the ability to learn compared to the other three cornerstones of RE. Findings indicated that by building rich files of rolling stock with pictures and stories, new mechanics without experience could learn from past experiences of other mechanics (learning basis). One of the perceived concerns was the (lack of) involvement of the train drivers and train managers in the MPS. Besides technical failures, operating errors also cause unexpected failures, but a structural feedback loop seems to be missing (learning target). The collection and disclosure of data and information for learning purposes was minimal (training, formalisation). Another concern raised was the sustainability of the MPS in the long-term and the involvement (and resilience) of other stakeholders on a network level, e.g. suppliers and supply chain operations who are not yet aligned to the MPS, which operates 24-h a day (learning target).

### *12.5.5 Resilient Performance in Corrective Maintenance of Rolling Stock*

The initial design of the MPS was focused on quick responses to unexpected failures of rolling stock, inspired by lean thinking. Case results confirm this, as illustrated by the higher scores on the ability to respond, although further improvements can be realised in this ability. Nevertheless, resilience consists of four abilities, which are not independent of each other (Hollnagel 2011). The four abilities can be considered as functions, and understanding how these functions are related is essential for managing them. The right balance of the four abilities of resilience is context dependent. Responding to actuals is very important for firefighters or emergency rooms where lives are at stake and events are difficult to predict. However, most of the time, this is not the case in corrective maintenance of rolling stock. Many failures do not directly impact safety or reliability, or additional controls are in place which prevents major disasters. The need to respond as quickly as possible, like firefighters, seems less important than being prepared for different kind of failures as not all unexpected failures have a direct (hazardous) impact on train operations and its passengers.

As our results showed, improvements can be made in all four abilities. However, it is important to focus on those abilities which provide the most value to reliable performance in a specific context. Based on the case results, Fig. 12.7 presents a proposal of rebalancing the four abilities for resilient performance in corrective maintenance of rolling stock in the pitstop case.

Although the main function of corrective maintenance is to respond to unexpected failures and defects, the need for a quick response is due to the nature of the failures, and the controls already in place, less important for improving resilience then anticipating future developments (e.g. weather forecasts) and the monitoring of critical components. The latter is also supported by new developments of predictive maintenance techniques and methods (Tiddens 2018). If implemented correctly, organisations should be able to predict failures based on the information collected

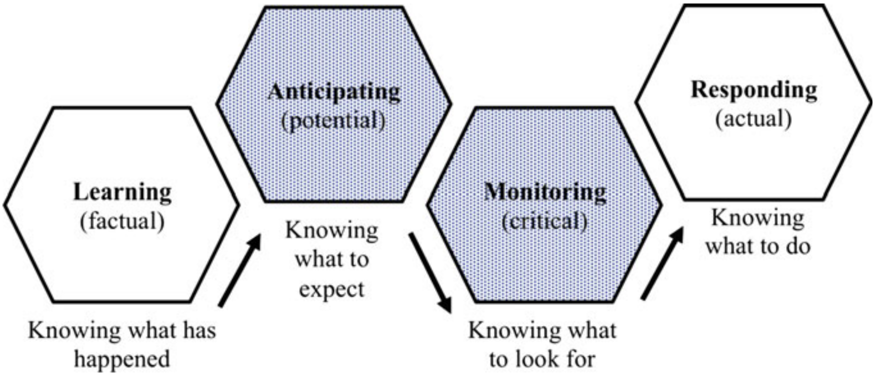


**Fig. 12.7** Four abilities in the context of corrective maintenance of rolling stock for reliable performance

through condition monitoring (Veldman et al. 2011). So, even though corrective maintenance is focused on responding to unexpected failures in operations, it can certainly benefit from more monitoring and anticipation in order to respond more effectively to unexpected failures. These new insights emerged from the application of the RAG method.

### *12.5.6 Key Inhibitors for Resilient Performance in Rolling Stock Maintenance*

Based on the analysis of the transcribed interviews, documentation and field observations, two important inhibitors were identified which may prove to be critical in achieving resilient performance. The first inhibitor concerns the capability to share information among stakeholders in the MPS for decision-making. Exemplary findings are the lack of transfer of information between mechanics in different working shifts, the need for data analysis on defects and failures for better forecasting, knowledge sharing between mobile maintenance teams and the MPS team located at the maintenance depots and the importance of a single source of truth to ensure accurate and reliable (configuration) information. The handover (and transfer of knowledge) among different shifts of mechanics confirms the observation as also identified by Patterson et al. (2004) in their research in healthcare.

A second inhibitor that emerged from the case is the collaboration of internal and external stakeholders in the network of corrective maintenance to achieve resilient performance. For example, the involvement of train drivers, train managers, system engineers, reliability engineers, mechanics and suppliers in learning from unexpected failures is essential to monitor and anticipate future failures. The need for balancing the abilities for resilient performance in rolling stock maintenance from a network perspective corresponds to the need to focus on resilience on a network level (interorganisational), and the observation that a system must be recognised as a whole where the dependencies among the parts is critical for overall performance (Hollnagel 2011). The case results underline the need for such a holistic view.

## 12.6 Discussion and Conclusion

The NS expects more unexpected failures as a result of the introduction of new rolling stock in an already highly utilised railway system. Managing these failures is of critical importance for reliable asset performance. One of the challenges of maintenance management was to determine if the current corrective maintenance system has the capabilities to cope with an expected increase of unexpected defects of rolling stock in the upcoming years or that further improvements are required.

A comparison between the characteristics of emergency healthcare and corrective maintenance showed that the studied contexts are highly comparable which suggested that the concept of RE may also apply to corrective maintenance of rolling stock in order to cope with the expected increase of unexpected defects of rolling stock. While the abilities of RE were recognised in the case study, measurements also revealed that there is still untapped potential for resilient performance. Potential that can be released to improve maintenance performance or to allow more complex maintenance actions. Two inhibitors were identified from the case which needs further research attention as they may prevent resilient performance in corrective maintenance; the effective use of configuration and failure data and the need for a holistic system perspective on corrective maintenance.

Although RE is recognised in corrective maintenance of rolling stock, as illustrated by several examples, it has not yet been formally accepted as a management standard. To increase further adoption of resilience in corrective maintenance, RE needs to be formally recognised as a contributor for reliable train services by management and further translated into policies and standards. This acknowledges the observation of Righi et al. (2015) who states that no reports were (yet) found in companies stating the need for using RE. By improving resilience of corrective maintenance, the resilience of the total railway system can be enhanced to ensure and maintain reliable train services to its passengers.

By comparing the findings of an Emergency Department (Nemeth et al. 2011), dealing with unexpected failures of 'human' assets, and the findings of the MPS, dealing with unexpected failures of 'physical' assets, further similarities may be discovered which might indicate the need to adopt resilience as a new design paradigm in corrective maintenance. Risks identified in the ED, as reported by Nemeth et al. (2011) include conflicting agendas, poor coordination among departments, constrained staff and a poor grasp of ambulatory care as a system. These risks can also be partly recognised when analysing the concerns found in the MPS, such as a lack of a holistic perspective of the system, limited availability of technicians and poor communication between team shifts.

This study contributed to theory by replicating and adapting RE for corrective maintenance of rolling stock and provides maintenance practitioners guidance on how to measure current resilience and identify improvement areas. The results of this research are specific to this case study but may serve as guidance to other asset-intensive maintenance organisations in increasing their potential for resilient performance in corrective maintenance. The adoption of RE in corrective maintenance of rolling stock encouraged the researchers to adopt the concept in future research to increase the reliability of complex rolling stock introductions.

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