Infrastructure Robustness for Railway Systems

PER NORRBIN\textsuperscript{1,2*}, JING LIN\textsuperscript{1} and ADITYA PARIDA\textsuperscript{1}

\textsuperscript{1}Division of Operation and Maintenance Engineering, Luleå University of Technology, 97187, Luleå, Sweden
\textsuperscript{2}Sweco Rail AB, 97324, Luleå, Sweden

(Received on January 11, 2016, revised on March 28, 2016)

Abstract: In the railway industry, most maintenance approaches are based on certain “specified conditions”, e.g., RAMS (Reliability, Availability, Maintainability and Safety) and Risk. But the reality is more complex. Instead of the assumed conditions, “unfavorable conditions” may occur from either natural or operational causes, where robustness can be an effective approach. To adequately consider “unfavorable conditions” and to reduce “uncertainties” in railway maintenance, this study conducts a holistic examination of railway infrastructure robustness. It gives an overview of robustness and discusses some relevant studies. It then develops a new road map for railway infrastructure robustness, including a novel definition and a new framework of robustness management, based on continuous improvement. It explores the opportunities of applying the road map to the infrastructure of railway systems and outlines some practical concerns and remaining challenges for future research. The results provide guidelines for other research into robust infrastructure in railway maintenance.

Keywords: maintenance; railway infrastructure; robustness; continuous improvement

1. Introduction

According to the European program Horizon 2020, multifaceted challenges in transport infrastructure include: 1) growing needs to make infrastructure more resilient to keep pace with the increasing mobility needs; 2) reducing the impact of infrastructure on the environment; and 3) dealing with declining resources to maintain and upgrade transport infrastructure. New design and maintenance approaches must be developed to handle these issues, as current methods are inadequate \[1\].

In maintenance practices of railway systems, most attention has been placed on RAMS (Reliability, Availability, Maintainability and Safety) study, which consists of safety and availability requirements \[2, 3\]. In Sweden, a popular area of study is RAM4S which incorporates supportability, sustainability, and security \[4, 5\]. The approaches to the maintenance of railway systems have changed significantly over the last century with a shift from an emphasis on technology to techno-economic considerations \[6, 7\]. Today, various maintenance strategies are applied in an integrated way depending on the criticalities and cost-effectiveness of a particular infrastructure. With new requirements generated by the increasing complexity of both the infrastructure system and operating conditions, these strategies continue to be developed \[8\].

The major drawback in current approaches is that they all assume certain “specified conditions” \[2\]. The reality is more complex; conditions are frequently “unfavorable” and
may require a different approach. For railway systems, “unfavorable conditions” stem from both natural and operational causes. In the case of the former, for example, in northern Sweden, the infrastructures operate in harsh conditions, including snow, ice and extreme temperatures ranging from -40°C to +25°C. Such naturally occurring “unfavorable conditions” often lead to time delays and economic losses. As for the latter, in the same region of Sweden, the regulations governing the axle load have recently increased from 22.5 tons to 30 tons because of changing transport needs; an even higher axle load limit (32.5 tons) is being tested. These new operational requirements demand continuous improvement and upgrades on the original track. Obviously, such operationally caused conditions are not “favorable” to the original track system: they will create more Rolling Contact Fatigue (RCF) problems and increase the degradation of the track infrastructure [9].

Resilience studies can improve the ability of an infrastructure to withstand disturbances caused by various “uncertainties” [10-12]. To this point, most studies have considered extreme events, including natural events like earthquakes or floods, and man-made events, like deliberate attacks on infrastructures [13-16]. Some argue studies considering resilience to extreme (natural and man-made) events should focus on adaptation measures and strategies to ensure seamless transport and user protection [1]. However, both naturally caused and operationally caused “unfavorable conditions” which do not belong to extreme events need to be studied as well. This represents a significant gap in the research. Research on the resilience of infrastructure is generally divided into two perspectives: rapidity or robustness. The former is defined as how fast the system can return to a high functional level, and the latter expresses the ability to resist specified disturbances so at least some functionality can be maintained. The two are not mutually exclusive, however, as rapidity is influenced by robustness. This represents a second gap in the literature; infrastructure robustness must be studied considering “unfavorable conditions”.

In railway systems, robustness studies have mainly been aimed at timetable management to handle delays (including secondary delays) within the system. Yet according to the statistics from the follow up system of the Swedish Transport administration (Trafikverket), LUPP, on total delays for the year 2015 show that more than 30% of the root cause of delays are due to non-robust infrastructures. Accordingly, railway infrastructure robustness is now attracting the interest of both industry and government. In Sweden, railway infrastructure robustness is becoming a pivotal area of government concern, being reported in the yearly review, regarding the condition of the railway assets [17]. In the Netherlands, the governmental infrastructure manager Pro Rail is conducting a project dedicated to achieving a “more robust and punctual rail network”; the idea is to minimize the impact of disturbances by making the infrastructure more robust [18]. In a recently published EU project report “SUSTRAIL”, researchers use a fuzzy way to describe railway infrastructures robustness, noting, for example, that “sometimes the limits of operation can be exceeded” [19]. However, the area lacks clarity (no clear research scope, definition, etc.) and the topic is not handled in a holistic manner. This precludes the achievement of a robust railway infrastructure able to face the multifaceted challenges of the future transport system.
This study takes a holistic approach to railway infrastructure robustness, considering “unfavorable conditions” in a bid to reduce “uncertainties” in railway maintenance. It proposes a new road map, including a new definition and research framework, to guide further research.

The rest of this paper is organized as follows. Section 2 presents an overview of robustness and mentions pivotal studies taking a continuous improvement point of view. Section 3 proposes a novel definition of infrastructure robustness with a focus on railway systems. For clarification, it compares relevant research concepts: robustness and traditional reliability, resilience and risk. Section 4 develops a new framework, which we term the House of Robustness Management (HORM), featuring continuous improvement in infrastructure robustness. Section 5 explores some opportunities in and practical concerns of the railway industry. Section 6 offers concluding remarks and suggests areas for further research.

2. Robustness Overview and Robust Infrastructure Related Studies

This section provides an overview of the robustness field and cites several studies of robust infrastructure. These form the foundation of the proposed road map described in sections 3 and 4.

2.1 An Overview of Robustness Fields

<table>
<thead>
<tr>
<th>Research Fields</th>
<th>Definitions of Robustness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control engineering</td>
<td>Insensitivity to uncertainty of a control system in input and model assumptions [20, 21].</td>
</tr>
<tr>
<td>Statistics</td>
<td>Insensitivity to small deviations in the assumptions [22, 23].</td>
</tr>
<tr>
<td>Computer science</td>
<td>Fault tolerance [24, 25].</td>
</tr>
<tr>
<td>Operations research</td>
<td>Solution that remains functional with changing operational scenario [26].</td>
</tr>
<tr>
<td>Decision making theory</td>
<td>Extent to which a system is able to maintain its function when some aspect of the system is subject to perturbations [27].</td>
</tr>
<tr>
<td>Economics</td>
<td>Ability of a model to remain valid under different assumptions [28].</td>
</tr>
<tr>
<td>Quality engineering/Product development</td>
<td>Small variability in a system’s function under various noise conditions [29, 30].</td>
</tr>
<tr>
<td>Biology</td>
<td>Ability to maintain performance in the face of perturbation and uncertainty, a well-established property of living systems [31, 32].</td>
</tr>
</tbody>
</table>

In the past 20 years, robustness studies have been conducted in various research fields, including but not limited to: control engineering, computer science, quality engineering, operations research, decision making theory, economics, and biology. As shown in Table 1, the definitions and research focuses vary across research fields.

In general, robustness is used to describe the “ability” of a system (or a model) to maintain its function (or performance) despite disturbance (incl. faults or perturbations). All robustness studies aim to reduce uncertainties.

The approaches of robustness studies include: 1) statistics driven models from input to output (e.g., control engineering, statistics, computer science, operations research, decision making theory, and economics); 2) physical characteristics driven design or...
optimization of a complex system or an item (e.g., quality engineering/product development, and biology); and 3) their integration (in many situations, both the statistics models and the physical characteristics need to be considered simultaneously).

Considering the complexity of different systems and their special characteristics, management of robust infrastructure requires knowledge from different research fields. To date, robustness studies are still being developed in separate fields. None of the results from the above fields can be directly used for infrastructure robustness.

2.2 Current Status of Robust Infrastructure Related Studies

Currently, six research topics are related to infrastructure robustness: robustness of structures, robustness of infrastructure in extreme events, robustness in risk management, robustness in maintenance, robust road networks, and robustness of train timetables.

As mentioned above, infrastructure robustness has not yet been studied in a holistic manner; therefore, its development requires knowledge from different research fields. In this study, we argue infrastructure robustness requires continuous improvement. Following the continuous improvement procedure proposed by Dr. W. Edwards Deming [33], the infrastructure robustness management process can be divided into four stages: Plan (P), Do (D), Study (S), and Act (A). When the Plan, Do, Study, Act procedure is applied to robustness, we can derive the following objectives for each stage:

- **Plan**: identification of the robustness requirements (incl. acceptable functionality in relation to disturbances, likelihood of “unfavorable conditions” and the impact) and data requirements, definition of infrastructure system, and design of the work process;
- **Do**: data collection, verification and analysis, execution of the robustness management process;
- **Study**: construction of key performance indicators (KPIs) for robust infrastructure management;
- **Act**: optimization of robust infrastructure management.

Table 2 shows the current research status of these topics, including the definitions and research focuses of each, from a continuous improvement perspective.

*Research focuses for Plan, Do, Study, Act are marked with “X”.

Present studies on the robustness of structures include solutions for structures to withstand damage or disturbances without collapsing [34], or for robustness to be measured and evaluated in a suitable way [39, 40]. The former aims to identify the robust requirements and make robustness management plan (P); the latter aims to set up KPIs (S).

Robustness studies examining the effect of extreme events on infrastructure look at different types of infrastructure and interdependent infrastructure in pre and post disaster situations. They consider how the infrastructure can resist and absorb extreme events and adapt to post disaster circumstances from both quantitative and qualitative aspects (P) [13, 41]. The area builds on the strengths and weaknesses measured by, for instance, robustness, risk and reliability. In particular, these studies focus on the development of KPIs (S).
Table 2: Current Status of Pivotal Robust Infrastructure Related Studies

<table>
<thead>
<tr>
<th>Topics</th>
<th>Represented Definitions</th>
<th>P*</th>
<th>D</th>
<th>S</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness of structures</td>
<td>Ability of a structure not to be damaged by events like fire, explosions, impact or human errors to an extent disproportional to the original cause [34].</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Robustness of infrastructure in extreme events</td>
<td>Ability to resist specified disturbances or perturbations so that at least some functionality can be maintained [13].</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Robustness in risk management</td>
<td>Ability to withstand a certain amount of stress with respect to the loss of function of the system [35].</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robustness in maintenance</td>
<td>Ability to handle uncertainty in model input [36].</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Robust road networks</td>
<td>Extent to which, under pre-specified circumstances, a network is able to maintain the function for which it was originally intended [37].</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Robustness of train timetables</td>
<td>Ability of a timetable to withstand design errors, parameter variations, and changing operational conditions [38]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Robustness studies of risk management for infrastructure follow the same principles as robustness studies of extreme events. The objective is to identify risk and determine how infrastructure robustness is influenced by it (P)[35].

Studies of robustness in maintenance look for maintenance plans able to handle the uncertainties in predicting deterioration of infrastructure while balancing structural performance and cost; thus, the research focus is on evaluating the accuracy of the maintenance plan (P, S) and creating optimization decision models (A). Note that the objective is not the behavior of the infrastructure [36, 42].

The study of robust road networks is a well-established industrial application, covering all stages of the PDSA process. However, there is no established process for the continuous improvement of robustness within the area. Vulnerability is the main focus and is regarded as the antonym of robustness; i.e., a vulnerable network is not robust and vice versa. In this application area, research contributions mainly include the identification of vulnerability related factors and their impact (P), data analysis (D), and vulnerability improvement (A). A network robustness index (NRI) is used to evaluate the performance of traffic and travel time (S) [37, 43, 44].

Robustness of train timetables is another common topic in industry. So far, such studies look for multi-objective optimization solutions by balancing asset efficiency, robustness (delay resistance) of a timetable, etc. Most studies are simulation-based. Although these studies cover almost the whole PDSA process, as discussed, there is a lack of research on root causes of delays, i.e., non-robust infrastructure in railway [38, 45, 45, and 46].

As Table 2 shows: 1) in different topics, robustness has different definitions and research interests; 2) no results from any topic can be directly applied to railway infrastructure; 3) most studies have limited research on specified stages in a continuous
improvement process, but as we argue, continuous improvement is essential to the robust infrastructure management of railway systems.

3. Novel Definition of Railway Infrastructure Robustness

This section introduces a novel definition of infrastructure robustness. It begins by explaining the key elements of the definition in section 3.1 and goes on to clarify it in section 3.2.

3.1 Railway Infrastructure Robustness

As discussed in section 2.1 and 2.2, currently, the definition of infrastructure robustness is not clear for railway systems; in addition, the research scope and topics are vague. There is an urgent need to take a holistic approach to infrastructure robustness of railway systems, one that considers “unfavorable conditions” and seeks to reduce “uncertainties” in railway maintenance.

For the purpose of developing a new road map, we define the infrastructure robustness of railway systems as the following: the ability of railway infrastructure to maintain an acceptable level of functionality in the presence of specified disturbances for a specified time period. In the following sections, we break this definition down into its four key elements (see Fig.1): ability to perform, functionality at an acceptable level, specified disturbances, and specified time period.

![Figure 1: Key Elements of Infrastructure Robustness of Railway Systems](image)

3.1.1 Ability

Like other robustness related definitions, those for infrastructure robustness describe some kind of “capability” that should be evaluated in both quantitative and qualitative ways to get a comprehensive measurement; this requires knowledge of statistics, maintenance, quality, mechanics, etc.

3.1.2 Acceptable Functionality

The most basic function of railway systems is transporting people or goods from one point to another. Different parts of the system have different contributing functions to fulfill the service needs of transport. The basic function of the infrastructure of railway systems is to allow rolling stock to pass safely and in a timely fashion according to plan with acceptable deviations.

The acceptable level of infrastructure functionality should be decided by stakeholders (incl. infrastructure manager, railway companies) and customers (incl. railway companies, rolling stock owners) according to existing agreements. Functionality can take various forms, e.g., train speed, train delays or punctuality, etc.
3.1.3 Specified Disurbances

In this study, disurbances refer to “unfavorable conditions” which raise uncertainties about the ability to maintain functionality at an acceptable level. To determine the robustness of railway infrastructure, relevant disurbances should be identified. The likelihood of their happening must be minimal in the immediate future (if the probability is high, this becomes a reliability improvement problem). Note that extreme events like earthquakes, floods or deliberate attacks on infrastructure which are studied in resilience are not within the study scope. Finally, the robustness of an asset depends on the type of disurbance; if it is robust against mechanical wear, it is not necessarily robust against heavy rainfall.

3.1.4 Specified Time Period

The time period for robustness is specified but can be changed depending on the scope of the follow up. It can refer to the winter months, the latest snowfall, or any lifetime calculation span, e.g. running distance for wheels. With changing calculation spans, today’s specified disturbances can become tomorrow’s required operational conditions. For instance, 10 years ago, the wagon axle load on the iron ore line in Sweden was 22.5 tons; thus, a load of 25 tons for one axle represented a disturbance. However, as the wagon axle load is now 30 tons, a 25-tonne axle load no longer represents a disturbance. In other words, the requirements of infrastructure robustness can change with time.

3.2 Definition Clarification

Table 3: Clarification of Robustness, Reliability, Resilience, and Risk

<table>
<thead>
<tr>
<th>Considerations</th>
<th>Robustness</th>
<th>Reliability</th>
<th>Resilience</th>
<th>Risk*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Functionality</td>
<td>Acceptable functionality</td>
<td>Required function</td>
<td>Normal functionality</td>
<td>Considered as a consequence</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Specified disturbance</td>
<td>No</td>
<td>Disruptions</td>
<td>Identified uncertainties</td>
</tr>
<tr>
<td>Time period</td>
<td>Specified</td>
<td>Specified</td>
<td>Not specified</td>
<td>Not specified</td>
</tr>
<tr>
<td>Railway Infrastructure</td>
<td>Yes</td>
<td>Railway industry e.g., EN-50126</td>
<td>Transportation infrastructure</td>
<td>In general</td>
</tr>
</tbody>
</table>

*: a dash means it is not applicable.

To clarify the novel definition of the infrastructure robustness of railway systems proposed in this study, definitions of robustness, reliability, resilience, and risk have been compared, as shown in Table.3. Specified definitions are following:

- Railway infrastructure robustness (section 3.1 in this paper): the ability of railway infrastructure systems to maintain an acceptable level of functionality in the presence of specified disturbances for a specified time period.
- Reliability [2]: the probability that an item can perform a required function under given conditions for a given time interval.
- Resilience [12, 14]: the ability to resist, absorb and adapt to disruptions and return to normal functionality. A resilient system has (1) reduced probability of failures; (2) reduced consequences from failures; and (3) reduced time to recovery.
• Risk [46]: the effect of uncertainty on objectives. Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.

As shown in Table 3, there are similarities but also clear differences among the above concepts. More specifically:

• Ability: All concepts concern an attribute of an asset, except for risk, which describes the impact and likelihood of an uncertainty.

• Functionality: Unlike robustness, reliability considers required function which normally has been decided in the design stage. Resilience considers the ability to stay in and return to normal functionality. Robustness includes the expectations of stakeholders in setting the standards for acceptable functionality, making it possible for alterations over time.

• Disturbances: Unlike robustness which considers a specified disturbance, or reliability which does not consider any disturbances, resilience considers all types of disturbances with an emphasis on extreme events. Risk reflects uncertainties which can be positive or negative.

• Time period: Robustness and reliability have a specified time period; resilience and risk have an unspecified time span.

• Railway Infrastructure: Unlike reliability and resilience, there is no definition of robustness for the railway industry. The novel definition proposed in this study aims to fill this gap. Risk has a general definition currently accepted in the railway industry.

4. Novel Framework of Infrastructure Robustness

To improve system robustness of railway infrastructure continuously, this section develops a new framework of robustness management. The pivotal elements of the House of Robustness Management (HORM) are: “Roof”, “Ceiling”, “Walls”, and “Floor”.

4.1 Roof of HORM

In the novel definition, the robustness of infrastructure systems can be evaluated in quantitative and qualitative ways. In the roof of the HORM, the goals of robustness management should be set to clearly guide the process.

First, robustness management goals will stem from the overall business goals of the organization and support their achievement. The Swedish Transport Administration (Trafikverket) views robustness as a pivotal part of its overall business goals, along with punctuality, capacity, usability, safety and environment & health. The achievement of robustness will support the overall business goals. At the same time, it will influence the goals of the other pivotal parts.

Second, robustness management goals should be hierarchically set, i.e., disaggregated down through different levels. For instance, when the robustness goal for the entire track system on level 1 is allocated down to level 2, it can be expressed as the robustness goals of the track and switches & crossings (S&Cs); when it moves further down to level 3, it becomes the robustness goals of rails, fastenings, sleepers and ballast, etc., separately. This is shown in Figure 1.

Third, the goals should be clear for the working group on each level. These goals should relate to and provide guidance for the working group’s role in, and contribution to, the total achievements of the organization.

Fourth, they should be disseminated periodically among the stakeholders and improved gradually.
4.2 Ceiling of HORM

The ceiling is one of the basic structures of a house. This understanding carries through to the HORM framework: the related infrastructure management guidance required to achieve robustness management goals and guide the overall process comprises the ceiling of the HORM. This guidance could include standards, work instructions, expert knowledge, and research reports.

Although there is no specific robustness management standard for railway infrastructure, related standards include international or regional standards, or those requested by a specified country/industry. For instance, reliability related standards should be considered as important references for robustness management. These include international standards (ISO\(^1\), IEEE\(^2\), IEC\(^3\), etc.), European standards (CEN\(^4\), ETSI\(^5\), etc.), and railway standards (UIC\(^6\), etc).

Work instructions present a sequence of steps to execute a task or activity. The Swedish Transport administration has several handbooks for performing various maintenance actions, for example, a handbook on how to clear snow from S&Cs [47]. These handbooks are important, not only to guide maintenance but also for the assurance of the management of robustness.

Expert knowledge can supply valuable guidance as well. This knowledge can come from group and/or individual experience. Sometime there is a need to consult experts with knowledge of special cases to support the creation of robustness strategies.

Research reports may include conclusions and suggestions which could guide robustness management. For instance, in Sweden many ideas come from research institutes (universities or research centers) or special reports from other organizations, including labs or consultant companies.

4.3 Walls of HORM

Following the thinking of continuous improvement developed by Edwards Deming, the four walls of the proposed HORM are Plan (P), Do (D), Study (S), and Act (A) [33]. The use of this PDSA cycle ensures robustness management is not only standardized but also improved gradually. The walls follow the robustness management goals (roof) and guidance (ceiling) and are supported by Information and Communication Technologies (ICT) systems (floor).

4.3.1 Plan

Plan is the start of the PDSA cycle. Main tasks involve robustness requirements identification, data requirements clarification, infrastructure criticality identification, and process construction for managing robustness.

In light of the novel definition of railway infrastructure robustness in section 3, “acceptable functionality”, “specified disturbances”, and “specified time period” need to

---

\(^1\) ISO: International Organization for Standardization.
\(^2\) IEEE: Institute of Electrical and Electronics Engineers.
\(^3\) IEC: International Electrotechnical Commission.
\(^4\) CEN: European Committee for Standardization.
\(^5\) ETSI: European Telecommunications Standards Institute.
\(^6\) UIC: International Union of Railways.
be decided in the Plan stage. Data requirements should be identified according to the robustness requirements. These, in turn, require the identification of infrastructure criticality, as different criticality may lead to different robustness strategies. Knowledge-driven approaches can be applied to identify criticality, including but not limited to: RCM (Reliability Centered Maintenance), FMECA (Failure Mode, Effect and Criticality Analysis), RAMS (Reliability, Availability, Maintainability and Safety), SIL (Safety Integrity Level), HAZOP (Hazard and Operability study), RCA (Root Cause Analysis), FTA (Fault Tree Analysis), FRACAS (Failure Reporting, Analysis and Corrective Action System), etc. The work process of robustness management should also be defined in the Plan stage.

4.3.2 Do

In the Do stage, the main tasks include data collection and verification, as well as execution of the process defined in the Plan stage.

Data collection and verification represent a key element of effective robustness management. Besides work orders, data could come from engineering design data, component test data, system test data, operational (and experience) data from similar systems, field-tracking studies in various environments, computer simulations, related standard and operation manuals, experience data from similar systems, expert judgment and personal experience, warranty data, etc. Robustness is concerned with uncertainties and unfavorable conditions that happen infrequently. However, incomplete or unreliable data will lead to misleading results in data processing (i.e. the conditioning and feature extraction/selection of acquired data) and decision making (i.e. the recommendations for robustness management actions based on diagnosis and/or prognosis, and then for maintenance prescription). Data verification ensures the data are able to evaluate the robustness of the railway assets in the Study stage. Finally, the execution of the robustness management process needs to be followed in this stage, so that the real situations can be assessed in the subsequent stage.

4.3.3 Study

In the Study stage, a system of key performance indicators (KPIs) should be set up to control and monitor robustness management. The KPI system consists of five different aspects, including KPIs for the robustness of railway assets, data quality assessment, resources, support systems, and the entire robustness management process. Economic considerations such as the life-cycle cost (LCC) should also be included.

Specific KPIs for measuring the robustness of assets are analyzed together with the related KPIs, for instance, RAMS, risk, and railway-specific KPIs like punctuality and train delays. The purpose of these KPIs is to evaluate the robustness of the assets. When evaluating data quality, KPIs for data collection and data processing are included.

Robustness management resources include: technical (hardware or software); human (personnel and competence) and organizational aspects (commitment, management style and preferences).

The effectiveness and efficiency of the support systems, including, for example, databases and computerized maintenance management systems (CMMS), must be periodically reviewed and controlled.
Finally, the entire robustness management process, the indicators for LCC, and the KPI system itself must be controlled and monitored.

4.3.4 Act

The Study stage reveals gaps between the present situation and the robustness management goals. This leads to the Act stage where improvements of performance are initiated to achieve the overall robustness management goals. This may include setting new goals. Benchmarking, new design or renewal, review and optimization of the robustness strategy, resource optimization, business process re-engineering (BPR), and KPI system optimization represent some possible improvement actions in this stage.

Benchmarking will shed light on the differences in the robustness of comparable assets in different operational and organizational scenarios.

The strategies for achieving robustness objectives need to be reviewed and possibly optimized. This can be done through various maintenance management techniques, for example, RCM, FMECA, RAMS, SIL, HAZOP, RCA, FTA or FRACAS.

Resource optimization seeks optimal solutions considering multi-objective criteria. This includes economic, technical (hardware or software), human (personnel and competency) and organizational aspects (commitment, management style and preferences).

BPR can be used to improve processes of robustness management defined in the Plan stage.

Finally, the KPI system needs to be optimized.

All the walls together form a sequential continuous process; for example, after the Act stage, the Plan stage is reviewed and improved. In this way, continuous improvements are ensured.

4.4 Floor of HORM

To improve the decision-making process in robustness management, data from various sources (e.g. product, production, maintenance, and business) must be collected, integrated, fused, and analyzed to transform them from information into knowledge. Therefore, data form the foundation or floor of the house. Most of the maintenance related data which will support various maintenance management techniques (for example, RCM, FMECA, RAMS, SIL, HAZOP, RCA, FTA or FRACAS) should have been recorded and stored in various management systems, such as CMMS, enterprise resource planning (ERP), special software for condition monitoring or other industry-specific supporting tools. Another important support area in this floor will be eMaintenance.

5. Discussion

In this article we have proposed a road map for railway infrastructure robustness, including a novel definition and a new framework of robustness management. Our definition brings clarity to a research area where “unfavorable conditions” may affect asset functionality, as expressed in the concepts of reliability, resilience and risk. The proposed framework for robustness management, termed HORM, provides a holistic view
of, and a continuous improvement process for, managing the robustness of railway infrastructure.

While the framework shows great promise, the concept of railway infrastructure robustness is continuing to develop. Remaining challenges include the following:

First, compared with the research topics of reliability, resilience and risk, infrastructure robustness requires further study from both theoretical and practical perspectives, especially for railway systems. This will include further details and case studies of qualitative and quantitative measures;

Second, of the four key elements discussed in section 3, “accepted functionality” can influence the identification of other elements;

Third, robustness management needs to be considered in a holistic way; HORM could be a guide for continuous improvement, but this requires top level management to take a holistic view;

Fourth, given the quickly developing areas of ICT, determining how to collect, integrate, fuse, and analyze data, as well as how to transform them from information into knowledge, will be an ongoing challenge in future robustness studies.

Fifth, the reality is complex, and “unfavorable conditions” are hard to identify and predict; insufficient knowledge or over-estimation may lead to high operational risks and costs;

Sixth, the determined robustness will necessarily be conditional, as it will depend on the identified conditions. An asset can be robust against one disturbance, for example, snowfall, but not robust against, for instance, heavy axle loads;

Seventh, trusted operation, interoperability with other modes and emergency preparedness should also be considered in railway infrastructure robustness.

6. Conclusions

To adequately consider “unfavorable conditions” and to reduce “uncertainties” in railway maintenance, this study conducts a holistic examination of railway infrastructure robustness by developing a new road map, including a novel definition and a framework. In this study, the novel definition of railway infrastructure robustness is proposed as: the ability of railway infrastructure to maintain an acceptable level of functionality in the presence of specified disturbances for a specified time period. This definition is useful, as it clarifies the research boundaries between robustness and reliability, resilience, and risk. The study develops a ground-breaking framework, named house of robustness management (HORM), based on continuous improvement to support infrastructure robustness management in railway; HORM consists of robustness management goals and guidance, a continuous improvement process, and support systems. Finally, the study considers the opportunities and challenges of applying the road map to railway infrastructure and provides guidelines for other research into robust infrastructure in different industries.
Acknowledgement

The authors thank Luleå Railway Research Centre (Järnvägstekniskt Centrum, Sweden), Sweco Rail AB and The Swedish Transport Administration (Trafikverket) for initiating the research study and providing financial support. We also thank Vivianne Karlsson, Stefan Jonsson, Anders Gustafsson, Professor Uday Kumar, Professor Per-Olof Larsson-Kräik, Dr. Christer Stenström and Dr. Stephen Famurewa (Luleå University of Technology) for their support and valuable discussions on this study.

References


Per Norrbin, Jing Lin and Aditya Parida


Per Norrbin is currently a PhD-candidate at the Division of Operation and Maintenance Engineering, at Luleå University of Technology, Sweden. His research area is Maintenance performance measurement and management. He has over 8 years of working experience within the railway industry. He is working as an asset management consultant at Sweco Rail since 2012. He has also worked in the maintenance department at the Swedish Railway Administration during 2008-2012.

Dr. Jing Lin is currently an associate professor in the Division of Operation and Maintenance Engineering, at Luleå University of Technology, Sweden. She obtained her PhD degree in Management from Nanjing University of Science and Technology, China. Dr. Lin’s research interests primarily lie in asset management, maintenance management, and reliability. She has published more than 50 peer-reviewed Journal and Conference papers and one monograph in related topics.

Prof. Aditya Parida is working in the Division of Operation and Maintenance Engineering, at Luleå University of Technology, Sweden. He obtained his PhD in Operation and Maintenance Engineering. His area of research is Asset Management, Maintenance Performance Measurement and model, RCM and eMaintenance. Besides teaching, he is actively involved in research and projects. He is the author of over 100 peer-reviewed Journal and Conference papers, besides three book chapters, and guest editor of seven special issues of International Journals.