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RAMS never dies! Applying the approach to IT/OT converged systems.

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The reliability of industrial systems is challenged by the increasing use of digital technology. One of these challenges is the reliability of digital technology (IT) in combination with physical assets (OT) - so-called 'IT/OT' converged systems or digitized systems. To ensure the reliability of physical assets, RAMS (Reliability, Availability, Maintainability, and Safety) methodology has become a widely accepted approach for designing and evaluating their performance. Unfortunately, the RAMS method is less common and evaluated in the context of digitized systems. This research discusses the application of a five-step RAMS method within the context of digitized systems. The outcomes of this RAMS method on a traditional system and a digitized system are compared using a real case study carried out with the main Dutch railway operator. The case study shows that the current RAMS application processes should be adapted for use on digitized systems. Several design principles are presented which can guide the better application of RAMS within a digitized environment.

Keywords: RAMS, operational technology, information technology, IT/OT convergence, digitized systems, asset management, railway.

1. Introduction

Physical assets are getting more digitized and interconnected. Up until the beginning of the 21st century, physical machines or systems were (electro)mechanical and could function as standalone systems. The design and maintenance of these systems were done by (electro)mechanical mechanics and engineers. These traditional systems are called operational technology (OT).

However, due to the ever-increasing pressure for more customization and faster access to markets and with the rapid cost decrease of chips and sensors, remote monitoring and interconnected systems become necessary. All this leads to the introduction of information technology (IT) aspects within the OT domain, this is called the IT/OT convergence of assets (Monostori, 2014). This IT/OT convergence of assets can also be seen as the digitization of assets. Generally, digitization has a broader scope and can also impact other domains, see for example Poliński & Ochociński (2020) for a study into the effects of digitization in the railway industry.

However, when applied to assets or systems these terms are similar and therefore, they are used interchangeably within this study.

Within the design of physical assets, the RAMS (Reliability, Availability, Maintainability, and Safety) methodology is commonly used because it helps to get an indication early in the design about the performance and quality of the system (Guthrie et al., 1990).

In the railways, the standard EN50126 specifies the RAMS process, herein the RAMS aspects are defined as (NEN, 2017). Several frameworks based on EN 50126 can be found in the literature such as Park (2010) and Szkoda & Kaczor (2017). An overview of RAMS applied in the railway sector can be found in the book of Mahboob and Zio (2018). It is stressed that RAM is a process that is continuous throughout the development phase of rolling stock (Muftic et al., 2015). Then, the effectiveness of RAMS can be measured by using lifecycle costing (LCC) (Kim et al., 2009) and Calle-Cordón et al. (2018) show the importance of RAMS in a study where they combine RAMS with an LCC analysis. Kumar then (2021) gives a case study on a RAMS analysis of an HVAC system.

Furthermore, a literature review by Pirbhulal (2021) shows, that for RAMS there is a need to develop tools or methods for RAMS in specific applications in line with this Muhammed Nor et al. (2022) state that a widely applicable RAMS methodology for the railway industry is currently missing.

On the other hand software for railway control and protection systems is harmonized through the EN50128 (NEN, 2011) which is being superseded by the EN50716 – cross-functional Software standard for railways (NEN, 2022). Nevertheless, these standards do not contain specific guidelines on how to implement RAMS on software products. This is a challenge since the most critical part of systems is software as González-Arechavala (2010) points out. They show that the current standards lack software RAMS evaluation. Due to the increasing digitization and IT/OT convergence, the impact of software on reliability is growing not only within safety critical systems. For non-safety critical software Chen (2017) shows that no consensus exists on how to deal with RAMS on non-safety-related software.

In practice, this IT/OT convergence poses significant challenges for the rail sector and specifically for a railway operator (RO) in the Netherlands as a (rail) asset manager and maintenance provider because traditional management methods coming from the field of either IT or OT don't seem sufficient to manage these digitized assets as more often problems seem to occur that should have been prevented by the used RAMS approach.

This challenge can be illustrated by looking at three rolling stock failures in the Netherlands that were in the news. These failures sometimes led to the stopping of the trains and thus had a high impact. In all cases, these failures were the result of unidentified software problems/issues. The causes of the errors were not clear and not easy to be found, (Sondermeijer, 2018; treinreiziger.nl, 2009, 2021).

In the presented research we will investigate how RAMS is still a valuable method for assessing the future performance of the design of IT/OT converged rolling stock. In a case study, the RAMS methodology that is being used within a Dutch railway operator is applied to an IT/OT converged system and this is compared with a more traditional OT system. Using this case study, we will identify several opportunities for improving the RAMS methodology on IT/OT converged systems.

2. Background

2.1. IT/OT convergence

Physical assets become more and more digitized, digitized assets are not only relying on traditional operational technology (OT) but also on information technology (IT). Multiple definitions of IT/OT can be found in the literature, for example, Kraeling and Fletcher give this definition which is clear and to the point: *"IT deals with interconnected systems and typically sharing of data, OT focuses on systems that are designed to do a specific task."* (2017, p. 3).

However, in multiple studies, the definition of Gartner is used, which states that *"Operational technology (OT) is hardware and software that detects or causes a change, through the direct monitoring and/or control of industrial equipment, assets, processes, and events."* (Gartner, 2021). This definition will be used in this research.

In academia, the concepts of IT/OT are often described as Cyber-Physical Systems (CPS), see for example: (Monostori, 2014), (Lee & Bagheri, 2015), (Hehenberger et al., 2016). Within the definition of CPS, "Cyber" refers to information technology and "Physical" aligns with operational technology. In this research, the term IT/OT is used. An IT/OT system can be characterized by three different parts: (1) mechanics, (2) Electromechanics and (3) Software.

First, the mechanics include actuators, sensors, etc. Second, the electrotechnical part provides the infrastructure to get the signals from the sensors to the programmable logic controller (PLC). Last, the software runs on a PLC and is programmed to work on the data from the mechanical inputs (Reussner et al., 2019).

2.2. Principal differences between IT and OT

In IT and OT converged assets and systems, different disciplines must work together to build good-performing, reliable and maintainable products. However, there are differences between the development of an IT system and an OT system, an overview of these differences is given in Table 1. It is because of these differences that OT engineers tend to focus on the hardware side of things, as we will show in this research.

Table 1: Comparison between OT and IT systems development, adapted from van Vliet (2008)

	OT	IT
Main cost phase	Construction phase	Design phase
Maintenance	Wear of the asset	Error detected late or requirements changes
Reliability	Wear and tear of the asset	Manifestation of errors already present
Building progress	Easy and visible	Difficult and often invisible
Impact of small change	Small	Considerable

3. Methodology

To get insight into how RAMS is used (or not) in practice on IT/OT converged systems we will conduct a single case study (Yin, 2013) within a railway operator in the Netherlands. Its main purpose is a process audit on the applicability of a specific RAMS approach within a rolling stock design, which can be used in the railway sector and may also apply to other domains. Moreover, the use of a single case allows for greater depth.

First, the RAMS approach that is used within the railway operator is introduced. Second, the different calculations that have been generated during the design and operational phase of the two systems will be compared, see Figure 1. Within this research, we are going to look at two different CCTV systems. One system is an analogue system which is fully self-reliant. The other system is an IT/OT converged CCTV system which is reliant on an IT system, specifically a TCP/IP backbone of a passenger information system.

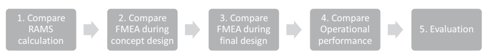


Figure 1: Overview of the research methodology, comparison of different aspects

3.1. RAMS approach steps

For this research, we have used a 5-step RAMS approach that is used in practice by a Dutch railway operator. This method gives insight into the reliability of the different systems. This method consists of the following five steps, see Figure 2. First, the performance of the current trainsets is analyzed (this can be either the train that is being overhauled or the train that is being replaced with a new one). Second, system performance that needs to be improved is identified and goals are set to achieve this performance improvement. Third, the so-called RAMS-LCC calculation sheets are updated with the right mission profile. These calculations contain a breakdown of the systems into parts or LRUs, according to EN 50126 (NEN, 2017). Fourth, the calculations are sent to the suppliers to be filled in with all the necessary information. With the MTBT of each component being the most important characteristic to calculate reliability. Also, several different other characteristics are entered into the calculation. This file then automatically generates the failure levels for each failure category (FC1, FC2 and FC3). Fifth, the different failure levels then can be compared to the set targets. If the targets are not the sheet is used to identify where there is room for improvement.

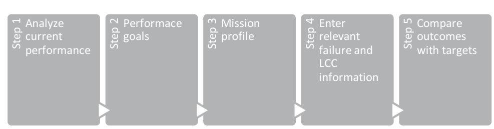


Figure 2: Overview of the RAMS process at the Dutch railway operator, based on EN5126 (NEN, 2017)

These different steps are documented using a spreadsheet. Within this research, we audit two different projects. First, a more traditional OT system and second an IT/OT converged system. We will not only look at the results in the Excel file but also the RAMS sections within the design documentation and we will study the operational performance of those different systems to show the effect of the RAMS calculations in practice.

4. Description of the case study

Two refurbishment projects are compared. The first, identified as “the old type” the concept design started in 2013 and the actual overhaul started in 2016. The other type identified as “the new type” concept design started in 2018 and the overhaul started in 2021. The trainsets run in fixed 4-car or 6-car formations. Both trains were designed in the 1990s and are traditional electromechanical concepts that consist of hardwired connections between systems. The protocols used within the trainsets to communicate are legacy/industrial protocols like Bitbus, RS485 and Wired Train Bus (WTB). During the overhaul, a Canbus network is added.

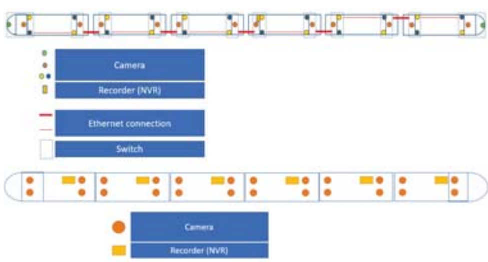


Figure 3: Sketch of old (top) and new (bottom) camera configuration, adapted from (RO, 2022a)[1]

The RAMS of the camera systems of the different trains are compared. These camera systems are added during the overhauls respectively in 2016 and 2021. See Figure 3 for a sketch of the configuration of these systems within the trainsets and

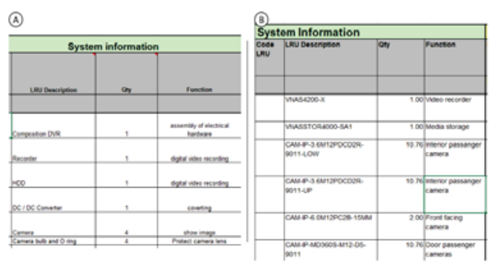
Table 2 for an overview of the differences between both. The old train type has a traditional camera system which uses analogue cameras and analogue video signals to a storage unit within each coach. The new train type on the other hand has digital cameras which communicate with one central storage unit within the train sets. The connection of these cameras to the central storage unit using an IP-based network that is part of the train's passenger information system or On Board-Information-System (OBIS). This network consists of several switches and a central computing unit (CCU).

Table 2: Overview of the differences in the camera system of the old and the new train type.

Category	Old	New
Input signal	Analogue camera’s	Digital camera’s
Integration level	Stand-alone system (OT)	Integrated with IT, so if IT fails, then OT fails as well.
Architecture	Simple architecture	Complex architecture
Viewing options	Images can only be viewed locally	Images can be viewed remotely and in real-time
Monitoring options	Monitoring through on train possible	Monitoring of only OT part on train possible, IT part needs special tooling
Image loss sensitivity	Camera’s more sensitive to image loss	Camera’s less sensitive to image loss
RAMS scope	Software is not part of the RAMS analysis	Software and IT network are not part of the RAMS analysis

5. Results

In Figure 4A an overview of the different parts of the camera system of the old trains is depicted and in Figure 4B an overview of the new camera system can be seen. Within these lists, the camera itself, the storage unit and the video recorder are mentioned. In the new system, a front camera is also added, in the old system and DC/DC converter and a digital video recorder (DVR) composition are mentioned, this composition consists of the recorder, hard drive and DC/DC converter. In both situations, no mention is made of the connection between the cameras and the video recorder.


A

System information

LRU Description	Qty	Function
Composition DVR	1	assembly of electrical hardware
Recorder	1	digital video recording
HDD	1	digital video recording
DC / DC Converter	1	coverting
Camera	4	show image
Camera bulb and O ring	4	Protect camera lens

B

System Information

Code LRU	LRU Description	Qty	Function
	VNAS4200-X	1.00	Video recorder
	VNASSTOR4000-SA1	1.00	Media storage
	CAM-IP-3.6M12PDCD2R-9011-LOW	10.76	interior passanger camera
	CAM-IP-3.6M12PDCD2R-9011-UP	10.76	interior passanger camera
	CAM-IP-6.0M12PC2B-15MM	2.00	Front facing camera
	CAM-IP-MD360S-M12-D5-9011	10.76	Door passenger cameras

Figure 4: Overview of RAMS calculations of the camera system; A. old train (RO, 2016b); B. new train, (RO, 2019a);

In Figure 5A the focus during the concept design phase of the old system is on the failure modes of the system components. The interconnection and the software of these components are not mentioned. However, during the final design phase the interconnections (cables) are included within the failure modes, see Figure 5B. There is no mention of the software and the possible failure modes the software can introduce.

[1] RO documents are internal documents from the railway company and are mainly in Dutch, they might be provided in anonymous form in case of necessity by contacting the first author.

Figure 5: Identified failure modes of the old camera system; A. during concept design (RO, 2012); B. during final design (RO, 2016a).

Table 3 gives an overview of the main failure modes of the new camera system; these failure modes were identified during the concept design phase. In this overview, no mention is made of the failure of the network that is designed to transfer the images from the cameras toward the network video recorder (NVR). In this overview, a software fault is mentioned, indicating that a software error will lead to the non-recording of images and that an error will occur, and be reported consequently as a fault. (This error will then be presented to the driver in the driver cabin on the Train Control and Monitoring System (TCMS) display).

Table 3: Identified failure modes of the new camera system from the concept design report (RO, 2018)

Component	Failure mode	Failure diagnosis	Effect on system level
NVR	HW- of SW-failure	Error message (No Image, power supply and/or storage)	Images in a vehicle cannot be stored and/or no recording by one or more cameras
Storage medium (separate LRU, is not part of NVR)	Storage issues	Error message (No storage)	Images in a vehicle cannot be stored
Camera	Camera does not register images	Error message (No image)	The respective camera does not register an image
Camera	(Malicious) Obstruction	Error message (Tamper alarm)	The recording function of the respective camera is limited

During the final design phase more elaborate failure modes are presented, see Table 4. However, in this overview software failures are no longer present, so apparently, they cannot lead to a failure mode. However, on the communication between the cameras and the NVR and the NVR and the OBIS, a much more detailed failure analysis is included.

Table 4: Identified failure modes of the new camera system from the final design report (RO, 2022a)

Component	Failure mode	Failure diagnosis	Effect on system level
NVR	No communication with OBIS	Internal electrical or ethernet error	No error message to OBIS No metadata/vehicle number information is available on the screens No camera auto-configuration to record images due to the absence of consist-identification No alarm recording due to missing trigger
	Video data cannot be stored	Error internal electrical, Ethernet-, motherboard-, storage-, or temperature error	No images available No images can be sent to a remote location
	Internal temperature-control defect	Sensor defect error	Temperature monitoring is not available
	RTC battery defect	No battery or battery empty error	Wrong time due to missing power supply from internal RTC (only relevant if NTP issue by OBIS also fails)
Storage-module	No video recording on the storage-module	SSD- or temperature-error	No images available No images can be sent to the remote security center
Camera in the compartment or on the balcony	The camera does not display images	Internal camera error	No video streams available for recording No live stream available for SOC
	No communication with the camera	Internal camera communication error	No video streams available for recording No live stream available for SOC
	Manipulated images	Camera-obstructed	The camera does not point in the right direction Camera dome damaged or vandalized Recording of manipulated images
Front Camera	The camera does not display images	Internal camera error	No video streams available for recording
	No communication with the camera	Internal camera communication error	
	Manipulated images	Internal camera communication error	Recording of manipulated images
Docking station	Unable to view images	LEDs are off due to internal, or power supply	Remote evaluation of images not possible

Component	Failure mode	Failure diagnosis	Effect on system level
		error or CM Player cannot find the module due to a connection error	

5.1. Operational performance

In this section, the operational performance of the two different systems will be elaborated upon.

5.2. Old system

In Figure 6 the annual overview of service requests is given on the CCTV system of the old trains. NB. A service request is a repair request for a mechanic. In 2018 the performance was above the set reliability target. In 2019 performance increased but still, performance was insufficient. The main problems with this old system were caused by not meeting today's electrical standards. So, a hardware change was needed to meet the current electrical specifications of the trains.

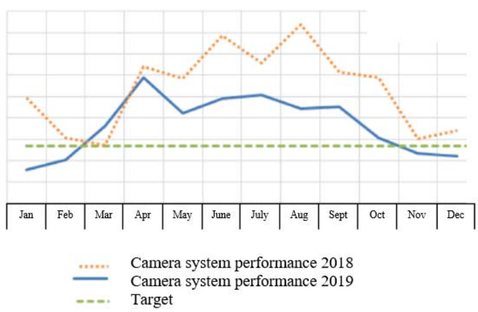


Figure 6: Annual overview of service requests on the CCTV system of the old train in 2018 and 2019 (RO, 2019b).

5.3. New system

In Table 5 the annual overview of service requests is given on the CCTV system of the new trains. As can be seen from this operational performance data is that the systems in practice don't meet reliability targets. However contrary to the old system, this poor performance was not caused by the system itself but due to problems with the IT network. If one of the network nodes fails, no CCTV data can be recorded. To solve this a pilot is underway to increase the reliability of the IT network nodes.

Table 5: Annual overview of service requests on the CCTV system of the new train in 2021 (RO, 2021)

RAMS Code	Average performance in last 12 months	Average performance in last 6 months	Target
1			0.00
2			0.00
3A	0.00	0.00	0.59
3C	0.52	1.55	0.20
Total	1.52	1.55	0.79

5.4. Old vs New

From the results above it becomes clear the effect of IT failures is not part of the reliability analysis of these systems. In the design of the old system, the effect of failures of the interconnection between the system elements is a small part of the system. In the new system, a more elaborate description of these aspects is made.

However, within the operational performance data, there are many error codes produced by the different trainsets indicating that there are no images recorded. Most of these issues are generated due to the network being unavailable.

This network is part of an ethernet-based network that was installed in 2014 to provide passengers with passenger information and Wifi. In the following years, many additions to this network have been done. Nowadays about 27 services run on this ethernet-based network (RO, 2022b). Ranging from passenger WIFI to safety critical systems.

Initially, this system was designed from an IT perspective which is different from the design perspective of the OT part. From the OT part, the focus is on generating a safe and reliable design. The IT part is more focused on generating the necessary functions.

6. Discussion

Assets becoming more and more digitized, however, the tools used for RAMS analysis are mainly focused on the performance of the OT part. Four main observations can be made from the case study.

First, the effects of software on system reliability are easy to be underestimated since the software failure modes are no integral part of the used RAMS methodology.

Second, a review of the operational performance indicated that a considerable number of failures seem to be related to the performance of the IT network and its interconnections. These interconnections between the systems should receive more attention during design.

Third, the engineers who do the evaluation are originally trained OT engineers and software has not been their main field of expertise, this can impact the proper detection and handling of software-related failures. A more multidisciplinary approach is necessary.

Finally, the optimization of system performance is very complex and thus it is nearly impossible to do such an analysis the first time right. A more thorough and iterative approach seems to be appropriate.

In this research, we have only investigated one specific case study which limits the general applicability of the results. It would be interesting to perform a comparative study with different railway operators or manufacturers.

7. Conclusions

By analyzing the RAMS methodology used within a Dutch railway operator this research has shown that RAMS is still a valuable method for assessing the future performance of the design of today's rolling stock. However, some improvement opportunities were identified for using the RAMS methodology on IT/OT converged systems.

(i) Tools/Methods: should be more focused on the incorporation of IT aspects.
(ii) Scope of the analysis: more focus should be on selecting the right scope for the analysis, either to include IT aspects or to purposefully exclude them.
(iii) Knowledge needed for analysis: a more multidisciplinary team of experts is needed.

(iv) Iterative process: IT aspects are sometimes hidden or not clearly visible, an iterative process is suggested.

In future research, we will investigate how to facilitate the adoption of the RAMS approach for IT/OT systems including the aspects mentioned above.

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