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An Industry 4.0 Technology Implementation Model for Rolling Stock Maintenance

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Abstract

Railway operators are being challenged by increasing complexity and safeguarding the availability of passenger rolling stock, bringing maintenance and especially emerging technologies into the focus. This paper presents a model for selection and implementation of Industry 4.0 technologies in rolling stock maintenance. The model consists of different stages and considers the main components of rolling stock, the related appropriate maintenance strategies and Industry 4.0 technologies considering the maturity level of the railway operators. Relevant criteria and main prerequisites of the technologies were identified. The model proposes relevant activities and was validated by industry experts.

Keywords: Rolling Stock; Maintenance; Industry 4.0 Technologies; Implementation Model

1. Introduction

Many innovative transport services have entered the market in recent years. Consequently, traditional transport modes are experiencing pressure from them. Examples include car-sharing, bike-sharing or E-scooters [1]. In comparison to the other transport services, rolling stock has the longest useful life of 25 up to 40 years. Trains must be functional, reliable, and economical over this long period. This can only be achieved by efficient maintenance to ensure the functionality of rolling stock [2]. Currently rail operators use predominately preventive maintenance strategies related to time or usage for strongly regulated components and components which can lead to malfunction of the train [3–5]. For all the other components reactive maintenance strategies are applied, which is a concern since parts are only repaired after failure. A fleet's legacy equipment limits the current maintenance tactics [5].

In the midst of fundamental changes brought about by Industry 4.0 technologies in maintenance, predominantly the industries with high value products such as aerospace, defense, nuclear, wind turbine industries but also machine tools industries are focusing on how to leverage these technologies [6]. Also in rail industry the potential of predictive maintenance is recognized. In particular for railway rolling stock, first predictive maintenance models for components e.g. for door systems [4] are investigated. On maintenance planning level studies show that predictive maintenance allows more flexibility as well as costs of can be reduced by more than 14 percent [3]. However, it is essential for the rail industry to improve their maintenance practices on a broad level to keep high safety standards, achieve a higher availability of rolling stock with less costs. Thus, there is a need that rail operators integrate Industry 4.0 technologies in their maintenance processes to overcome train availability issues as well as operation inefficiency of rolling stock.

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1.1. Purpose and delimitations

This paper provides a model for the implementation of Industry 4.0 technologies in rolling stock maintenance, taking into account the rail operators technological maturity level. The focus lies on electrified rolling stock for passenger transport because today, three-quarters of passenger rolling stock is electrified [7]. The mechanical systems are considered due to their long operation time of 15 to 20 years [8]. Furthermore, the paper is bound to Industry 4.0 technologies for maintenance processes and not any other processes.

1.2. Research approach

The research approach for the model development consists of the following four steps (see Fig. 1). First, a literature review is conducted based on the relevant research fields. It is continued by a questionnaire-based online survey of emerging technology implementation in rolling stock maintenance processes. Finally, the Industry 4.0 technology implantation model (I4.0TIM) is developed and validated by subject matter experts of rolling stock maintenance.

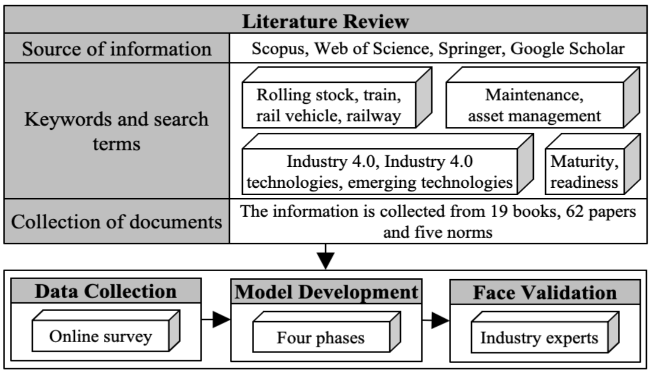

Fig. 1. Research roadmap

2. Related work

A literature review with regard to this study is carried out for the four main topics: namely, rolling stock, maintenance, Industry 4.0 technologies and maturity assessment. To determine which emerging technologies are particularly promising in maintenance, a systematic literature review is conducted. In the following sections the key findings of the specific research fields are presented.

2.1. Rolling stock

Especially the mechanical components and systems are in operation for the longest period of time and only receive a complete overhaul every 15 to 20 years [8]. Principally the components and systems can be divided into two categories: operational-relevant systems and systems for passenger rolling stock. The first-mentioned category is essential for the technical operation of rolling stock and thus forms the basic elements for rail operations. The running gear, drive technology, brake unit, pantograph and traction and buffer gear are responsible for the technical operation of rolling stock [9,10]. The interaction of all components enables the rail operation we know today. For passenger comfort, the second category assumes a central role and entails an increasing complexity of systems. In the past trains used to be equipped without sanitary facilities or heating, ventilation, and air conditioning, but today this is standard equipment for a passenger rail vehicle. The other systems in this group are the door system and indoor lighting system [9,10].

2.2. Maintenance in rolling stock

In recent years, preventive maintenance has established itself as the preferred strategy in rolling stock maintenance [11,12]. With this strategy the rail companies manage to reduce the risks of failure, but at the same time the maintenance costs increase with regular preventive maintenance [13]. The frequency of preventive maintenance is primarily determined by laws and regulations [11]. Current main trends in rolling stock maintenance are condition-based maintenance (CBM) and predictive maintenance. Although these strategies have been known for decades, the rail vehicle industry is struggling to implement these [14]. A further reduction in rail vehicle maintenance costs is achieved at the next level, for instance in predictive maintenance. This is the case because only limited additional implementation costs are required for the upgrade. Although modern maintenance strategies are now available, rail vehicle companies struggle to implement these, while the rail industry also finds digitalization challenging [14].

2.3. Industry 4.0 technologies in maintenance

The conducted systematic literature review is based on the suggested approach by [15] and has been modified for this research. The systematic literature review has revealed that nine emerging technologies are essentially used in maintenance. The four technologies, namely big data and analytics, Internet of Things, cloud computing and virtual reality are cited most frequently. These are outlined in seven of the 17 documents. Following closely are augmented reality and cyber security with six appearances each. Furthermore, cyber-physical systems, artificial intelligence and additive manufacturing are mentioned as promising technologies in maintenance. Furthermore, the review revealed the following seven main benefits associated with the implementation of Industry 4.0 technologies in maintenance: increase in the system reliability, cost reduction, time savings, acquirement of a competitive advantage, increase in the quality assurance, increase in the transparency of assets and an increase for the safety of employees.

2.4. Maturity assessment

Numerous maturity models are identified from the literature. Several maturity models exist in different disciplines like economics, the natural sciences or humanities [16]. These models are usually a supporting instrument to evaluate and ascertain the present state. For this study Industry 4.0 maturity models are considered. Since the scientific literature often does not clearly distinguish between the terms “maturity” and "readiness", readiness models are also included in the analyses. Finally, the following three models are selected for closer examination due to their appropriate scope and structure:

- *Model 1:* Industry 4.0 maturity index [17]
- *Model 2:* A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises [18]
- *Model 3:* The degree of readiness for the implementation of Industry 4.0 [19]

It is evident that all three models are practice oriented. All three are intended to assist companies in identifying a possible path for Industry 4.0.

2.5. Summary

It is evident from the literature that the rail industry struggles to apply the latest maintenance strategies. There are Industry 4.0 technologies available for integrating and improving maintenance processes. Furthermore, there is no model or method provided for the rail industry for Industry 4.0 technology implementation in maintenance. Thus, there is a research gap, which this research addresses through the results of an online survey and the development of a model.

3. Online survey

A survey was conducted to empirically evaluate the effects of the maturity level for the implementation of Industry 4.0 technologies in maintenance as well as to quantify the benefits of implementing Industry 4.0 technologies as determined by the literature review. The questionnaire is structured into the following four parts:

1. Digitalization in general in the rail industry (presence of the topic, current status, comparison of departments)
2. Implementation of Industry 4.0 technologies in rolling stock maintenance (technologies, benefits, challenges, effects, current status, area, and system of implementation)
3. Technological maturity level in the rail industry (Industry 4.0 technologies implementation progress)
4. Information on the surveyed participants (region of experience, industrial sector, field of transport)

The survey was sent to 220 subject matter experts, of whom 82 fully answered the survey. Regarding the effect of the Industry 4.0 technology implementation, the most common answers state that there is a general improvement in maintenance. For example, one participant responds that it is "easier to maintain all components". On the other hand, it is pointed out that the general improvements in maintenance resulted in fewer maintenance activities. This is demonstrated by the fact that according to the answers it is possible to switch from a preventive to a predictive maintenance strategy. Besides the general maintenance improvements, increased reliability is indicated. In principle this refers to the reliability of components such as brake systems as well as to improved reliability in maintenance planning. Positive effects are also achieved during troubleshooting. A respondent states that the "disturbance can be overcome immediately, and passengers are not harmed because the condition of the monitored component is clear". The positive effects during troubleshooting refer primarily to time reduction and the improved diagnostic capability for troubleshooting. Furthermore, the responses reveal an increased efficiency. The justification for an increase in efficiency is primarily because of quality data collection, which enables advanced analytics. Hence, maintenance processes become more efficient. A significant influence is also noted regarding the costs. According to the subject matter experts, cost is reduced for the maintenance costs as well as for the subsequent costs of downtime is achieved. It is also mentioned that there are overall cost reductions for life cycle costs. The positive impacts and effects are evident form the responses. However, some negative experiences are also described. It is reported that there are difficulties with implementation, due to the lack of sufficient knowledge and experience in such implementation.

4. Industry 4.0 Technology Implementation Model (I4.0TIM)

This section presents the model which is developed to supports rail operators with different degrees of technological maturity, to implement Industry 4.0 technologies in rolling stock maintenance. Requirements for the model are the consideration of individual preferences regarding the system and emerging technology selection, the consideration of the maturity level, modularity, and support of a continuous flow of the information by specifying and harmonizing inputs and outputs. The I4.0TIM is modularly structured and influenced by the results of the literature review and the online survey (see Fig. 2). Four phases are integral to the I4.0TIM and are presented in the following sections.

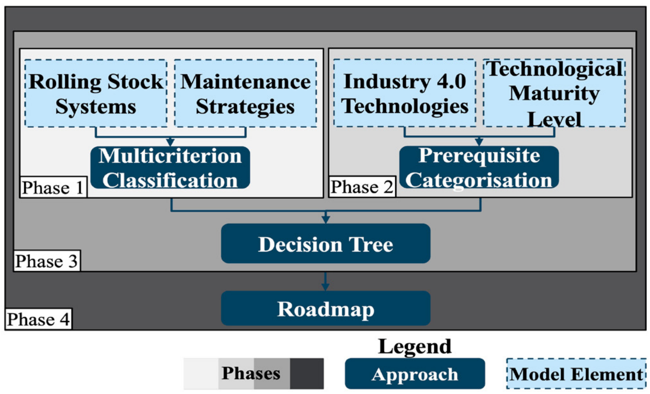

Fig. 2. Industry 4.0 Technology Implementation Model

4.1. Phase 1: Selection of the maintenance strategy for rolling stock systems

The objective of the first phase is to define suitable maintenance strategies for the rolling stock systems. A multicriteria classification is applied as an approach to determine the possible systems based on [20]. The classification is built on nine different steps. First, the rolling stock systems are defined, which needs to be examined for this purpose. The main mechanical systems identified by the literature review are used as basis (see Section 2.1.). The next step is to define the criticality criteria. The aim is to compile a detailed classification of the systems, which is to be used as a reference for the maintenance strategy to be applied.

For rolling stock maintenance the following criteria, c_i, are considered as relevant:

- c_1: Impact on health and safety
- c_2: Influence for rolling stock reliability
- c_3: Influence for rolling stock availability
- c_4: Impact on environment
- c_5: Maintenance costs
- c_6: Existence of alternative systems
- c_7: Impact for customers
- c_8: Failure frequency
- c_9: Impact for rail operation

Safety, reliability, availability, ecology and economy are key elements in rolling stock maintenance [10]. Furthermore, the redundancy of the systems is considered. For example, most rolling stock are equipped with two pantographs, so in the case of failure, another can be deployed. After all, customer satisfaction is a key factor in operating passenger rolling stock. Moreover, it is relevant to include failure frequency as a criterion. This is justified by the fact that train systems indicate various failure frequencies. For example, a system can only fail once a year or daily during train operation. The key issue here is the impact of the failure on rail operations. Therefore, the failure of the system leads to penalties as it has an impact on the entire rail operation. Once the criteria are determined, the direct insertion method is followed to determine the relative importance of the individual criteria is ascertained [20]. The result is provided in Expression (1).

$$\begin{aligned} &l_1)\ c_1,\ c_4 \\ &l_2)\ c_6,\ c_7 \\ &l_3)\ c_5,\ c_8,\ c_9 \\ &l_4)\ c_2,\ c_3 \end{aligned} \quad (1)$$

After determining the relative importance of each criterion, the weighting is ascertained for each level. To simplify the evaluation of the criteria, [20] suggest a value of one for the first level which represents the lowest weighting. An overview of the weight assignment for all criteria is contained in Table 1.

Table 1. Weight assignment to the criteria

Description	Assignment			
Level l_i	l_1	l_2	l_3	l_4
Criterion c_i	c_1, c_4	c_6, c_7	c_5, c_8, c_9	c_2, c_3
Weight w	1	2	3	5

To get the criterion vector for the previously defined list (see Table 1), the list is inverted. For the nine criteria, the vector is:

$$(c_2, c_3, c_5, c_8, c_9, c_6, c_7, c_1, c_4) \quad (2)$$

Thus, the weighting of the criteria in Table 1 and the criterion vector defined in Expression (2) results in the following weighting vector:

$$(5, 5, 3, 3, 3, 2, 2, 1, 1) \quad (3)$$

In the next step a uniform scale for the criteria is defined. For this purpose, each criterion is divided into the same number of categories, d. These represent the different degrees of possible criticality for a system to the criterion being assessed. Five degrees of criticality are defined for the application. The different degrees of criticality are graded as very high, high, normal, low and very low, which are assigned to the corresponding values 4, 3, 2, 1 and 0 [20].

To get the numerical values of the evaluation the criticality index, I_c is determined [20]:

$$I_c = 100 \cdot \frac{\sum_{i=1}^{n}(d_i \cdot w_i)}{d \cdot \sum_{i=1}^{n} w_i} \quad (4)$$

where:
I_c = criticality index
n = number of criteria
d = number of criticality degrees of the criterion
d_i = criticality degree of a certain system according to the criterion, c_i
w_i = weight of the criterion, c_i

The last part is to classify the nine previously determined criticality indices I_c. The simplest strategy is represented by reactive maintenance, whereas smart maintenance is the most complex one and involves the most effort for implementation. The purpose of Table 2 is to assign the criticality index, I_c, to the maintenance strategies. The thresholds are derived from the survey results. Only rolling stock systems, s_i, are further considered with a quite high criticality index, I_c, because they should be prioritized for the emerging technology implementation.

Table 2. Maintenance strategy selection according to criticality index I_c

Maintenance strategy	Criticality index I_c in [%]	Further consideration
Smart maintenance	$I_c \geq 50$	Yes
Predictive maintenance	$35 \leq I_c < 50$	Yes
CBM	$20 \leq I_c < 35$	No
TBM	$10 \leq I_c < 20$	No
Reactive maintenance	$I_c < 10$	No

4.2. Phase 2: Selection of Industry 4.0 technologies based on the maturity level

The objective of this phase is to extract the Industry 4.0 technologies that are appropriate to the current technological maturity level of the I4.0TIM user. The determination of the technological maturity level is necessary for the subsequent approach. Therefore, each user of the I4.0TIM individually determines its technological degree of maturity based on the main prerequisites of the emerging technologies. The determination is facilitated through a questionnaire.

The approach of this phase consists of three parts. At the beginning, the prerequisite weighting factor is determined for each of the three prerequisites of the emerging technology, t_i. The prerequisite weighing factor, wf, is derived from the different characteristics in Table 3. These are intended to determine how difficult it is for the I4.0TIM user to fulfil the prerequisite. The characteristics are concentrated on the five most important ones to make the approach as simple and user-friendly as possible. The costs for fulfilling the prerequisite are essential. The next characteristic estimates how complex it is for the user of the I4.0TIM to implement the prerequisite in the company due to the different degrees of complexity of the characteristics. Therefore, the required knowledge and experience are also included in the characteristics. This may already be available in the company or it has to be acquired externally.

Table 3. Overview of the characteristics

Index a_i	Characteristics
a_1	Costs to fulfil prerequisite
a_2	Complexity for the implementation of the prerequisite
a_3	Required know-how for the prerequisite
a_4	Dependencies of other systems for the prerequisite
a_5	Duration of the implementation for the prerequisite

Likewise, prerequisites for the fulfilment of the system may depend on other systems. In a sense, certain systems have to be implemented beforehand to fulfil the prerequisite. The last characteristic to be covered is the time required for the implementation. Due to the previous characteristics, such as complexity or knowledge and experience, the time varies to fulfil the prerequisite. Each of the five characteristics has four categories on an ordinal scale from negligible to high/long. A weight of 0, 1, 2, and 4 is assigned to each of these categories. The last category of the scale is weighted higher, emphasizing the difficulty of the highest category. To obtain the prerequisite weighing factor, *wf*, Equation (5) is applied:

$$wf_{t,p} = \frac{\sum_{i=1}^{n} a_i}{max\ points\ possible} \quad (5)$$

where:

$wf_{t,p}$ = weighting factor of technology, t, and prerequisite, p,
n = number of characteristics
a_i = characteristic, i

After determining the three prerequisite weighing factors, $wf_{t,p}$, of an emerging technology, t_i, the total weighting factor, WF_t, is calculated. As shown in Equation (6), the total weighting factor, WF_t, is the sum of the three corresponding prerequisite weighing factors, $wf_{t,p}$:

$$WF_t = \sum_{p=1}^{n} wf_{t,p} \quad (6)$$

where:

WF_t = total weighting factor of technology, t
n = number of prerequisites
$wf_{t,p}$ = weighting factor of technology, t, and prerequisite, p

Finally, it is necessary to verify whether the selected emerging technology, t_i, can be applied at the current technological maturity level. To determine whether this is the case, the total weighting factor, WF_t, is compared with the current technological maturity level in Table 4. The cut-off values resulted from the maturity levels appearance, calculated based on the questionnaire results.

Table 4. Total weighting factor WF_t assignment

Technological maturity level	Total weighting factor WF_t
Maturity level 5	$WF_t \geq 2.70$
Maturity level 4	$2.20 \leq WF_t < 2.70$
Maturity level 3	$1.60 \leq WF_t < 2.20$
Maturity level 2	$1.00 \leq WF_t < 1.60$
Maturity level 1	$WF_t < 1.00$

4.3. Phase 3: Decision regarding implementation

The objective of phase 3 is to determine whether the selected Industry 4.0 technology, t_i, is appropriate for the implementation of the selected rolling stock system, s_i. The developed decision tree diagram is depicted in Fig. 3. The general part of the decision tree involves determining whether all the necessary preparations for implementation are available. The second part of the decision tree examines performance in more detail to achieve a final decision. An essential activity of this part is to analyze maintenance performance indicators thoroughly for arriving at the final decision regarding the implementation.

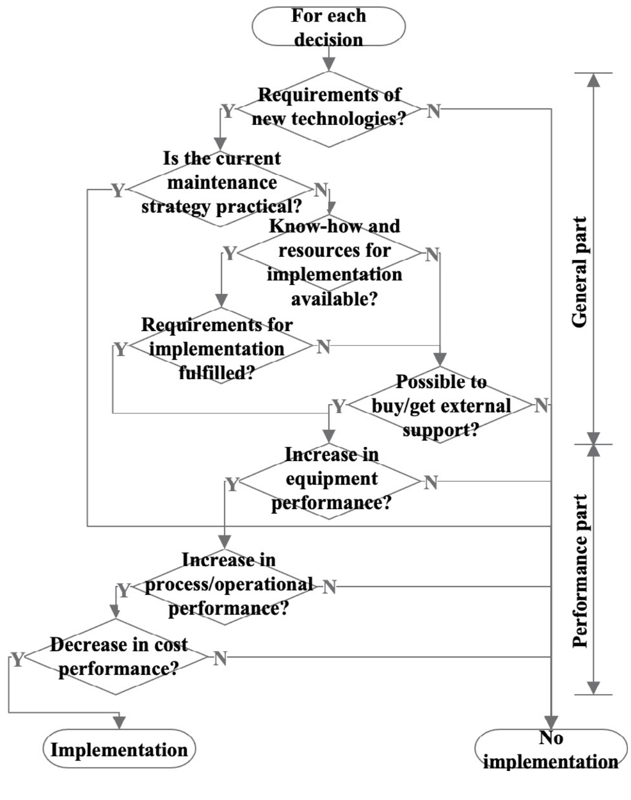

Fig. 3. Decision tree diagram

4.4. Phase 4: Future programme

Depending on the number of technologies and systems that have been identified through the phases, several technologies and systems may be appropriate for this phase. The first milestone is about preparing for implementation. The technology requirements must first be implemented.

Afterwards, a solution concept for the individual case has to be developed, followed by the building of a prototype. It is recommended that the test is first performed on one rail vehicle. In the case of successful tests, it can be rolled out to the entire fleet before full integration across fleets occurs. The second milestone is the implementation. In terms of challenges, the following list provides an overview about the main challenges:

- Lack of corporate strategy
- Limited financial resources
- Lack of qualified personnel and competences
- Lack of technological prerequisites
- Lack of information regarding implementation

The final milestone considers what benefits will be experienced after technology integration. The main benefits to be expected are reductions in costs, an increase in system reliability, quality assurance and competitive advantages.

5. Face validation

Face validation is conducted to whether the I4.0TIM and its associated four phases could add value to rail operators' maintenance processes. For this study, eight subject matter experts validated the model after attending a presentation given by the researchers. The face validation questionnaire employed within this study is based on an extract from the case study conducted by [21] and encompasses five questions. The overall feedback of all participants about the developed model is positive so that the I4.0TIM is considered to be a suitable solution. Concerning the strengths of the model it is emphasized that the model is an effective solution for the industry. The relevance and logical description of the model is considered very good by five participants and good by three. For the applicability of the model, it is assessed as very good by four and good by three participants and fair by one participant. The results consequently reflect the predominantly positive feedback of the participants and confirm the importance of the model for rail operators. Areas identified for future research is the practical implementation of the model to assess the cost of applying the model in practice and the associated difficulty level of implementation for rail operators with a very low maturity level.

6. Conclusions and outlook

This paper presents the I4.0TIM which has the potential to support rail operators for their decision of implementing Industry 4.0 technologies in their rolling stock maintenance processes. So far, there are no uniform approaches that allow the implementation of Industry 4.0 technologies by rail operators considering their level of maturity. An extensive literature review and an online survey are used to develop the I4.0TIM. Face validation of the I4.0TIM with subject matter experts provides evidence that the model assists rail operators in their decision to implement Industry 4.0 technologies and is an effective solution for the industry. For further improvement the I4.0TIM has to be tested practically by rail operators.

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