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Digitalization of Rail Freight Transport

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Purpose: *Increasing demand for freight transport is in direct contrast to climate policy goals. Rail freight can reduce overall emissions if it builds up more market share. To achieve this, the rail sector needs to increase its competitiveness with other modes of transport using digitalization. Thus, the aim of this work is to analyze digitalization measures in rail freight transport.*

Methodology: *As we consider our problem as a multi-attribute decision problem, we measured the importance of different digitalization measures regarding its contribution to improve the overall competitiveness of rail freight transport based on an AHP-approach.*

Findings: *Based on a systematic literature review we identified 17 digitalization measures, which we grouped into four categories: automated train operation, digital maintenance, automated marshalling, and digital access to rail transport services.*

Out of those categories, automated train operation should be more focused on, followed by digital maintenance. Competitiveness is based on quality improvement, cost reduction and performance improvement out of which quality improvement was considered most important. Thereby reliability as well as time flexibility were considered as equally important by the experts.

Originality: *The paper gives a detailed overview of the status of digitalization measures available in rail freight.*

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1 Problem Background and Research Question

Freight transport is an essential prerequisite for the economy in Germany. In addition to the increasing volume of traffic, transport routes are also becoming longer and longer as a result of advancing globalization (Destatis, 2021). The current trend of increasing freight traffic in Germany is also supported by forecasts, as transport performance is expected to increase by around 40% by 2030 in relation to 2010. These developments in freight traffic are causing significant transport and environmental policy problems, as traffic is increasingly emitting greenhouse gases that are harmful to the climate (BMVI, 2017). However, looking at the modal split, we see that road freight transport is the dominant mode of transport in Germany, accounting for 70.2% of total transport performance, while rail freight achieves a market share of just under 19% (BMVI, 2021c).

To reduce greenhouse gas emissions and energy demand in the transport sector, a modal shift towards more environmentally friendly modes of transport is necessary in addition to a reduction in traffic. Shifting traffic from road to rail is therefore a viable strategy to mitigate the impact of freight transport on climate change, as rail transport (or intermodal transport) is more environmentally friendly than road freight transport only (Pinto et al., 2018). This modal shift can contribute to a more environmentally friendly freight sector (Rickenberg, von Mettenheim and Breitner, 2012; Lobig, Liedtke and Knörr, 2017). Accordingly, strengthening rail freight transport and increasing rail's share of the modal split is an integral part of meeting climate targets (Kagermann, 2021). However, rail's share of freight traffic increased by only 2.8% between 2000 and 2017 (Allianz pro Schiene, 2020). The targets set by the German government in 2002 regarding its sustainability strategy for 2015 have been missed. These targets envisaged an increase in the share of rail in the modal split to 25 % (UBA, 2021). Thus, to cope with the increasing freight traffic and to avoid bottlenecks in the rail freight infrastructure, significant investments in the infrastructure are necessary. Another approach to making better use of the existing rail freight infrastructure can be *digitalization* (Böttger, 2020).

The use of digital technologies offers the opportunity to increase efficiency and safety while reducing environmental impact without limiting mobility (Nemtanu and Marinov, 2019; Kagermann, 2021). Current developments show that road freight transport is benefiting from the increase in freight traffic demand and can further expand its share in terms of the modal split (Zanker, 2018). In this context, it is particularly relevant to consider digitalization, which can play a key role in increasing rail efficiency (Kagermann, 2021).

The focus of this work is the collection, presentation, and structured analysis of current digitalization measures that increase the competitiveness of rail freight transport compared to road freight transport. Increasing the competitiveness of rail should lead to an increase in market share in the freight market and thus support the desired modal shift. The research question is defined as:

Which digitalization measures should be prioritized in rail freight transport to increase the competitiveness of rail as a mode of transport compared to road?

Answering the research question is of theoretical relevance to gain an overview of current digitalization measures in rail freight. A summary of current measures also contributes to a new understanding of the topic in the literature. By identifying these very digitalization measures, future research can examine individual measures more thoroughly based on the overview to be compiled. Furthermore, by prioritizing the digitalization measures, conclusions can be drawn for practical application.

The remainder of the paper is as follows: After having presented the problem background and the research question, section 2 provides the conceptual background which includes digitalization in general as well as in logistics and in rail freight. Furthermore, benefits and drawbacks of digitalization are presented as well as the notions of competitiveness are understood in this paper. Section 3 introduces the methodological approach, which is based on a systematic literature review for identifying the digitalization measures and the Analytical Hierarchy Process (AHP) for the systematic comparison of those. The results of our analysis are shown in section 4 and discussed in section 5. Section 6 provides a critical reflection and answers to the research question, limitations as well as an outlook for future research.

2 Conceptual Background

This chapter defines the term digitalization and addresses its impact on logistics and rail freight. Based on the main advantages and weaknesses of rail freight, a framework for its competitiveness is developed.

2.1 Digitalization

Due to the vagueness of the concept of "digitalization", the term is predominantly not precisely defined in the literature (Srai and Lorentz, 2019). To understand digitalization in a general context, it is helpful to also look at the terms “digitization” and “digital transformation” (see also Figure 1). This is of particular importance in a German context, since "Digitalisierung" is used here as a term for all three concepts. These terms can also be understood as steps that build on each other and are each used according to their scope of application.

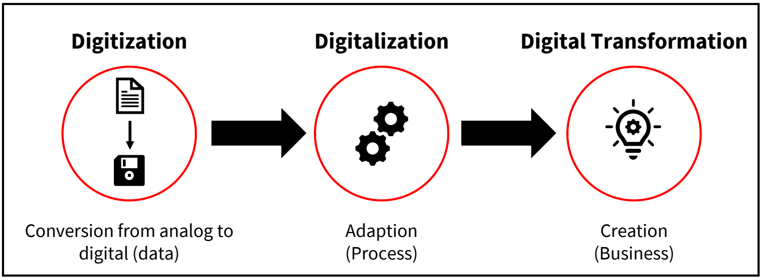

Figure 1: Digitization, Digitalization and Digital Transformation (own representation based on (Maltaverne, 2017; Bumann and Peter, 2019))

The first step “digitization” is limited in its scope of application, as it focuses on the conversion of analog to digital data. The second step "digitalization" then describes the use of digital technologies and thus, for example, the digitalization of a process. In terms of its scope, the third step “digital transformation” is the most encompassing since it affects not only a single process but the entire company or even industry. In digital transformation, previously performed activities are rethought to create new sources of value (Bumann and Peter, 2019).

2.2 Digitalization in Logistics and Rail Freight

Digitalization in the context of logistics is known as "Logistics 4.0", which describes the full availability of digital information on objects and actors in the logistics industry. With the help of digitalization, established logistics companies have the opportunity to realize various opportunities and potential for success (Becker et al., 2019). However, there are certain requirements that digital logistics must fulfill, such as increasing security, reliability, or even speed (Heistermann, ten Hompel and Mallée, 2017). In summary, logistics can be understood as one of application field of digitalization that has great potential. Many digitalization concepts such as Internet of Things (IoT) or autonomous driving are strongly linked to logistics, which is why it plays a central role in the implementation, but also in the design of digital methods and concepts (Wei and Noche, 2020).

Rail freight transport is only on the threshold of the first phase of digitalization, which is the introduction of new technologies. This situation can be explained by the poor economic conditions of rail freight transport, structurally expensive innovations and strategic advantages of other modes of transport (Müller, 2021). The digitalization of rail freight offers advantages such as the reduction of costs, transport times as well as the ecological footprint. On the other hand, the already existing network capacity of rail freight can be expected to increase reliability and flexibility (Enning and Pfaff, 2017; Zapp, 2018; Müller, 2021). Rail freight transport has lower emissions per tonne-kilometer compared to other modes of transportation, and increasing the competitiveness of rail would help reduce emissions in freight transport making it more sustainable (BMVI, 2017; DLR, 2017). The underlying definition of digitalization in this thesis includes the transformation of data as well as the design of processes with the help of the use of digital technologies in rail freight transport in order to achieve an increase in efficiency (Maltaverne, 2017; Bumann and Peter, 2019; Müller, 2021). Step 3 is not included in the definition because the area of digital transformation goes beyond the area of individual digitalization measures.

2.3 Benefits and Drawbacks of Rail Freight

An important advantage of rail freight transport is the low rolling resistance between the rail and the wheel (Meier, Sender and Voll, 2013). This results in the special suitability of rail for transporting large quantities and masses over long distances (Wannenwetsch, 2014). This energy efficiency also results in relatively low pollutant emissions in relation to the transport performance (Meier, Sender and Voll, 2013). A key weakness is the tie to the rail infrastructure, which very cost-intensive to build and maintain (Meier, Sender and Voll, 2013). Another disadvantage of rail freight is its strong dependence on predefined schedules. This leads to a further reduction in flexibility. In addition, the different requirements of the individual national railroads within Europe make for long border stops when transporting goods by rail (Gleißner and Femerling, 2012).

2.4 Competitiveness

We understand in this competitiveness as *“the sustainable and thus long-term ability of a sector to secure or expand market share through simultaneous attention to price and non-price factors”* (Martin, Westgren and van Duren, 1991; Bräkling, Lux and Oidtmann, 2020).

Market share in this context means the share of rail in relation to the total freight transport volume. According to Lee and Karpova, competitiveness consists of three parts: the goal(s), the method(s), i.e. how these goals can be achieved, and the framework conditions under which this process takes place (Lee and Karpova, 2018). Since this abstraction takes a national economic perspective which is not concrete enough for the rail freight industry examined in this work, it needs to be adapted. The three parts addressed plus the introduction of digitalization measures into the concept can be seen in Figure 2.

The framework conditions are to be omitted, as they are not relevant to the core of the study, since they are not influenced by digitalization measures and play a subordinate role in this paper. In the further course of the work, the methods will be referred to as criteria to avoid possible confusion during the implementation of the Analytical Hierarchy Process (AHP).

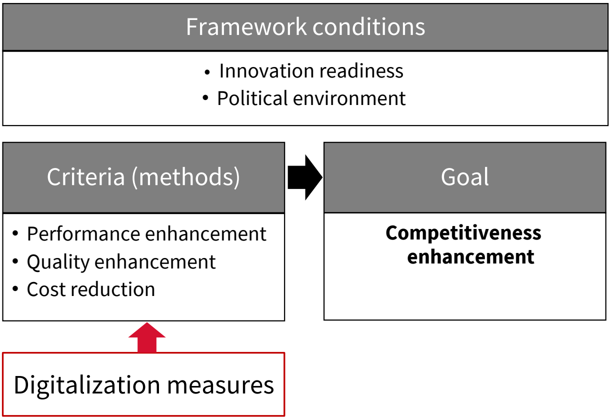

Figure 2: Representation of competitiveness (own representation based on (Gudehus, 2010; Lee and Karpova, 2018; Bräkling, Lux and Oidtmann, 2020)

Since the assessment of competitiveness, or the attractiveness of the offer, ultimately lies in the eye of the user or customer, the criteria will not be omitted (Feurer and Chaharbaghi, 1994). These represent the logistical factors used to decide which mode of transport provides the most utility (Gudehus, 2010; Bräkling, Lux and Oidtmann, 2020). However, it would not make sense to consider all criteria equally, since rail freight already has some advantages over road freight. For example, further emission reductions would not be particularly effective, as marginal returns would be low in terms of offer evaluation. Therefore, only those factors where rail is inferior to road transport will be examined (see 4.2).

3 Methods

This chapter presents the methodological approach consisting of a Systematic Literature Review to identify digitalization measures and an Analytical Hierarchy Process to evaluate those.

3.1 Systematic Literature Review

The methodological concept of the systematic literature review (SLR) aims at the compilation of a comprehensive literature review on a predefined topic by means of a suitable selection strategy (Carnwell and Daly, 2001; Kemmler et al., 2020). In the literature search, the keyword search is the most common method in practice, which is also followed in this work (Ely and Scott, 2007; Kemmler et al., 2020). The literature search is used to identify relevant secondary literature on the topic of "Digitalization measures in rail freight transport". This includes book chapters, journal articles, magazine articles, reports, and contents of websites. A total of five databases are used for the research work. These are Google Scholar, WISO-Net, Scopus, Web of Science, and the Bremen State and University Library. In addition to these databases, simple Google searches are also performed to extract relevant digitalization measures from Internet pages. To ensure a further high quality and reliability of the data, only those websites are used that originate from governmental institutions, represent corporate websites of actors in rail freight transport or are frequently cited in renowned scientific papers. Another step of the selection strategy is the definition of keywords. The search terms „digital*“, „Digitalisierung*“, „Automatisier*“, „Technologi*“, „Schiene*“, „Deutsche Bahn“, „DB Cargo“ were combined in different ways. Particularly with regard to such current and rapidly changing content of a subject area as digitalization measures, it is extremely important to ensure that the information to be procured is up to date (Brink, 2013). Therefore, only literature that is not older than 15 years is used in this work. Furthermore, the selection is made to exclusively German and English language works. For a classification of the relevance of the viewed sources for this scientific work, first the abstracts and conclusions are read. If a positive evaluation results from this consideration, a skimming of the complete contents follows. If another positive assessment for relevance is made after this step, the available literature is subsequently read in detail and the full information on the research objective is extracted. In the last step of the selection strategy, sources are to be included based on appropriate cross-references within the already identified literature. We identified 27 relevant sources in total, most of which were German.

3.2 Analytical Hierarchy Process

The digitalization measures which we identified in the literature (see 3.1) are evaluated with the help of the AHP by Saaty (1977) regarding their ability to increase the competitiveness of rail freight transport. The application of the AHP takes place in five successive steps (Saaty, 1977; 1980; Riedl, 2006; Goodwin and Wright, 2014), which are outlined Figure 3. In this paper, all five steps are applied chronologically to the decision problem.

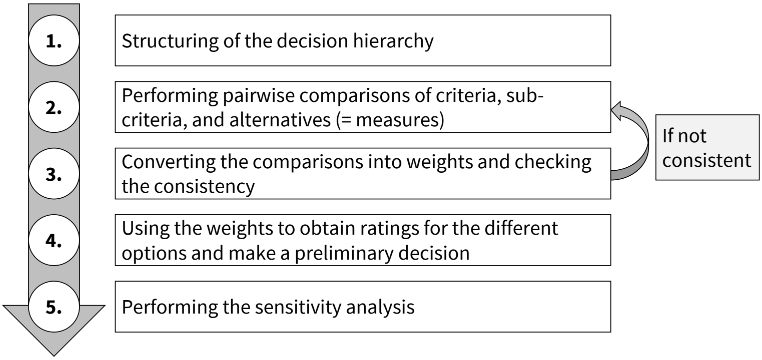

Figure 3: Flow chart of the steps of the AHP (own representation based on (Goodwin and Wright, 2014))

All steps of the AHP were carried out by the authors of this work, except for step two. For this purpose, two experts in the field of rail freight transport were interviewed, who will be referred to as Expert A and Expert B in the following. Expert A works for a company that develops transshipment systems in intermodal transport and Expert B works in the field of digitalization and automation for a large logistics service provider in rail freight transport. All steps from step two onwards are carried out in this work with the help of the online tool AHP-OS by Goepel (2018). For this purpose, the developed decision hierarchy is transferred to the tool, which then guides the user through all subsequent steps. To counteract a certain complexity of the handling with the AHP-OS tool during the pairwise comparisons, the experts were accompanied by the authors during this step in an online meeting. The tool offers the advantage that all calculations, such as the overall result with its intermediate results at the various levels, the consistencies, and the sensitivity, can be performed automatically and displayed clearly.

The experts first compare the criteria with each other in pairs and then the sub-criteria. Finally, the digitalization measures (= alternatives) are compared in pairs regarding their influence on the respective sub-criteria. For each comparison, the experts assign a score between 1 (=equal importance) and 9 (=the first object is absolutely dominant). The comparison results are transferred to matrices and then converted to weights, where the sum of the weights is 1 and the individual weights can be represented as percentages. The mathematical approach is based on eigenvalues (Saaty, 1987). The weights are calculated by dividing each value of the matrix by the corresponding column vector. The rows of the resulting matrix are added and divided by the column sums. The result of this calculation is a weight vector (Riedl, 2006). See Goepel (2018) for additional details.

4 Results

This chapter presents the results of the Systematic Literature Review - the digitization measures - in a structured way and presents the outcomes of the AHP.

4.1 Digitalization Measures

The SLR on digitalization measures in rail freight transport has revealed a large number of different measures. From a total of 27 identified measures, 17 were selected for further analysis. To be selected, the measure must a) conform to the stipulated digitalization definition (see chapter 2.2); b) have a sufficiently strong connection to rail freight transport and c) not be too similar to an already selected measure. The selected measures are assigned to 4 categories, which are based on a DB Cargo whitepaper on the topic of digitalization and automation of logistics in rail freight transport (DB Cargo, 2021b). Table 1 offers a clear representation of the selected measures and categories.

Table 1: Selected digitalization measures and categories

Categories	Digitalization Measure
Digital Access	Track and Trace
(see 4.1.1)	Geofence Control
	Wagon Data
	Modility
Automated Marshalling	Digital Automatic Coupler
(see 4.1.2)	Fully Automatic Bead Breaking Locomotive
	Yard Management Tool
	Automated Brake Test
Automated Train Control	European Train Control System
(see 4.1.3)	Fiber Optic Sensing
	Future Railway Mobile Communication System
	Digital Interlockings
Digital Maintenance	Camera Bridge
(see 4.1.4)	Wheelset Diagnosis
	Brake Sole Diagnosis
	Automated Switch Inspection
	Digital Fleet Management

4.1.1 Digital Access

The category of digital access can generally be understood as the provision of data and information. This provision can take place with the aid of platforms along the value chain and thus support companies in planning and controlling within rail freight transport (DB Cargo, 2021b). This information may include, for instance, the loading condition, temperature or humidity during transport (Meitinger, 2020). In the following, the services included in the digital access category will be discussed.

Track and Trace comprises the acquisition and transmission of location data and the recording of the cargo and wagon condition (Bruckmann, Fumasoli and Mancera, 2014). For this function, the freight cars must be equipped with GPS and telematics (Bosch, 2021; DB Cargo, 2021b). With the help of the GPS sensor and telematics, data on the position and condition of the freight car is transmitted every 10 minutes (DB Cargo, 2021b). This enables remote monitoring of the transport progress and thus better planning of the arrival of the freight car. In the future, other sensors can be installed to provide additional data. These sensors include temperature sensors, humidity sensors and sensors that monitor the status of the doors. All of these sensors enable even more comprehensive monitoring of the cargo and its condition (Meitinger, 2020; Bosch, 2021; DB Cargo, 2021b). Another measure is the service of **Geofence Control**. Here, the technology of geofencing is used. The principle of geofencing is that a virtual fence is drawn around a certain area (Reclus and Drouard, 2009). The freight cars are also equipped with GPS and telematics for this purpose (Verkehrsrundschau, 2021). As soon as the freight car enters the virtual fenced area, it is registered. This enables rail transport companies and customers to have an accurate overview of the number of freight cars within the fenced area (DB Cargo, 2021a). **Wagon Data** is a digitalization measure of DB Cargo AG. The freight cars are equipped with radio frequency identification (RFID) and near field communication (NFC) (DB Cargo, 2021). RFID technology offers the possibility of contactless and automated transmission of information and identification of objects using radio waves (Rosová, Balog and Šimeková, 2013). RFID and NFC thus make it possible to quickly identify a wagon, check the wagon number at loading points and track wagons, and record the wagon sequence of a freight train. These processes can run fully automatically thanks to the technologies used (DB Cargo, 2021). **Modility** is a German platform that is designed to facilitate bookings and intermediation for Combined Transport (CT). Access to intermodal transport is not just intended to strengthen CT, but above all to focus on rail as a mode of transport and thus make it more accessible (Kossik, 2021). By providing necessary information, the platform links two different groups of actors. Operators can market their transport capacities and freight forwarders can find and subsequently book them. Finally, it should be emphasized that Modility does not have any own transport responsibility, as this is passed on to the customers (Kossik, 2021).

4.1.2 Automated Marshalling

Automated marshalling with its automation and digitalization measures represents an important step in the advance of rail freight transport. Through a combination of the Train Formation System 4.0 and the development of the Freight Car 4.0, time-saving and more efficient shunting processes will enable optimization (Enning and Pfaff, 2017; Jäger, 2020).

The **Digital Automatic Coupler** (DAC) is a solution for moving the previously exclusively manual coupling process to the automatic coupling of freight cars (Borghini, Topal-Goekceli and Engelmann, 2021). Compared to the manual screw coupling, the DAC also connects the power, data and main air lines of the freight cars, thus ensuring important prerequisites for digitalization and automation in train formation (BMVI, 2021b). These features can lead to increased efficiency, time savings, increased productivity and safety, and an increase in the overall rail freight modal split (BMVI, 2021b). In addition, the DAC will enable an increase in capacity and performance in terms of the length of freight trains. In the future, the **Fully Automatic Bead Breaking Locomotive** (FABBL) will ensure a fully automatic bead breaking process in the train formation facilities. With the development and introduction, a completely driverless bead breaking operation should eventually be made possible (Eisenbahn-Bundesamt, 2021). The bead breaking process begins when the FABBL is attached to the freight car. This is followed by the release of the wagon securing device by the FABBL. After the removal of the wagon safety device, the FABBL is then ready to press the freight wagon over the hump (TH Nürnberg, 2017). The **YAMATO** decision support system, which is intended to facilitate the work of dispatchers in the train formation system with the aid of real-time data, information, forecasts, decision support and other analyses, can also generate a sustainable increase in efficiency through automated train formation. The digital evaluation of information in the planning cycle of the dispatchers in the train formation system ultimately enables an increase in productivity, quality, and punctuality of the operation. Other features that will bring benefits in the future include ensuring the stability of the entire transport network and minimizing the risk of additional costs incurred by previously manual errors (Nguyen et al., 2020). A digital brake display on the freight car and the associated digitalization measure of the **Automated Brake Test** offer potential for efficiency improvements in the train formation process. The brake checks that have been carried out manually in the past, could be bundled by digital control devices on both sides of the freight cars with the help of sensor technology and telematics information from the brakes and enable the wheeltapper to save physical and time brake checks (DB Cargo and VTG AG, 2019).

4.1.3 Automatic Train Control (ATC)

ATC offers several advantages over the conventional train control currently in use. The automated train monitoring can increase capacity on the tracks, as the technology allows trains to be spaced closer together. Another advantage is the reduction in the number of signaling systems and other trackside elements, which would reduce corresponding maintenance costs. In addition - depending on the degree of automation - personnel and energy costs can be saved (Schnieder, 2021a). Furthermore, computer-controlled driving is expected to reduce noise and mitigate wear and tear. The latter would reduce maintenance and repair costs for the drive and braking systems (Tasler and Knollmann, 2018). Higher levels of automation also require the appropriate infrastructure and technology. In Germany and Europe, these are to be provided by the **European Train Control System** (ETCS). Germany has been investing in ETCS since 2015 (BMVI, 2021a). However, only 320 km of German rail lines had been equipped with ETCS by 2019, with a further 1800 km of rail track to follow by 2023 (Eisenbahn-Bundesamt, 2017; DB Netz AG, 2020). In terms of track monitoring, Deutsche Bahn is currently testing **Fiber Optic Sensing**. This involves fiber optic cables that can measure changes in various properties, such as pressure or temperature. The sound patterns typical of certain events (moving train, running animals, tree breakage, etc.) are stored in a database, and when an incident occurs, the sound waves generated can be compared with those in the database. The localization is accurate to within five meters and can, for example, enable a timely warning in the event of an animal on the tracks (Pohl, 2018; Vidovic and Marschnig, 2020). For communication, the throughput rates of the current, 2G-based radio traffic are too low for the required data volumes and the latency times cause too great delays in interface communication. Therefore, as a measure in this area, a switch from GSM-R to the **Future Railway Mobile Communication System** (FRMCS) is supposed to be implemented. This standard is 5G-based and offers the correspondingly necessary performance in the areas of latency and throughput (Enning and Fratscher, 2017; Nitzschke, Wübbena and Rahmig, 2020; Schnieder, 2021b).

4.1.4 Digital Maintenance

Digital maintenance describes an area of digitalization in rail freight transport in which the reliability and resource efficiency of maintenance processes can be increased through the further development of procedures and the use of data with the help of certain technologies. In addition, the ability to generate forecasts can be enabled (Biedermann, 2019). As part of its Asset & Maintenance Digitalization program, DB Cargo is pursuing a four-stage model for the digital maintenance of its wagon fleet. The first stage describes the modular inspection. The second stage is condition monitoring. The third stage describes condition-based maintenance. The last stage involves predictive maintenance.

The first two digitalization measures within the Digital Maintenance category are **Wheelset and Brake Sole Diagnostics** using suitable technology. Specifically, **Camera Bridges** for external damage detection and transmission computers on the locomotives are used here. The camera sensor bridge can detect damage. The transmission computers are installed on the locomotives and transmit the necessary signals to the wayside. With the help of this data, an early assessment of the condition of a locomotive and an effective adjustment of the maintenance strategy with regard to the brake pads and wheelsets is possible (Müllerschön and Niggemann, 2018; Jäger, 2020; DB Cargo, 2021b). Another digitalization measure in this category is **Automated Switch Inspection**. Currently, switches are responsible for around 50% of disruptions in train operations. Seven cameras are used in this process, which are capable of synchronously recording the switches. The various laser measuring systems can measure the rail cross-sections as well as all guiding distances in the switches. As a result, there is no obstruction of other train traffic and timetables are hardly affected. The images and measurement results obtained are subsequently sorted with the aid of intelligent software and are then available to analysts for assessing the condition. The different angles of the images reveal all the details about the actual condition of the switches. The most striking advantages of this technology are on the one hand the increase of safety aspects in work processes and on the other hand an increased track availability (Eurailscout, 2021). Furthermore, a software solution for fleet control can be used within the framework of digital maintenance. **Digital Fleet Management** digitalizes the maintenance and maintenance order process in rail freight transport. The software solution enables around 3,000 locomotives and their individual components to be mapped digitally. In addition to this mapping, the software is then able to identify the nearest workshop for routine checks as well as potential malfunctions, which also has the necessary resources required for the repair (Boom, 2021). The last digitalization measure is the already mentioned **Camera Bridge** used for the detection and reporting of damages of freight cars. In this measure, the use of AI enables automated maintenance checks of freight fleets. The use of algorithms in AI image sensor data analysis makes it possible to deploy camera sensor bridges that automatically detect and report damage to freight cars (Jäger, 2020; DB Cargo, 2021b).

4.2 AHP Decision Hierarchy

The overall goal of the AHP methodology is to evaluate the selected digitalization measures in terms of their potential to increase the competitiveness of rail freight. We derived three top level criteria from competitiveness definition (see chapter 2.4) and from the logistics objectives as suggested by Gudehus and Kotzab (2012). The criteria include performance improvement, quality improvement and cost reduction. Each criterion is influenced by sub-criteria. These are only those criteria in which rail freight is currently inferior to road freight. Examples of such are transport time and time flexibility. The weakness of rail freight transport compared with road freight transport lies primarily in the long train formation times. This means that the expectations placed on rail freight with regard to transport times can often not be met (BVU, 2016; Stoll, Schüttert and Nießen, 2017). In rail freight transport, time flexibility is characterized by the fixed commitment to predefined timetables (Wannenwetsch, 2014) and the commitment to fixed travel times on the pre-selected train paths (Muschkiet and Ebel, 2013). This results in a certain limitation of rail freight, whereas road freight can act faster except in the case of congestion. Due to the large number of sub-criteria in combination with the pairwise comparisons, a single analysis of all 17 measures is too complex. For this reason, the previously established categories form the alternatives of the AHP.

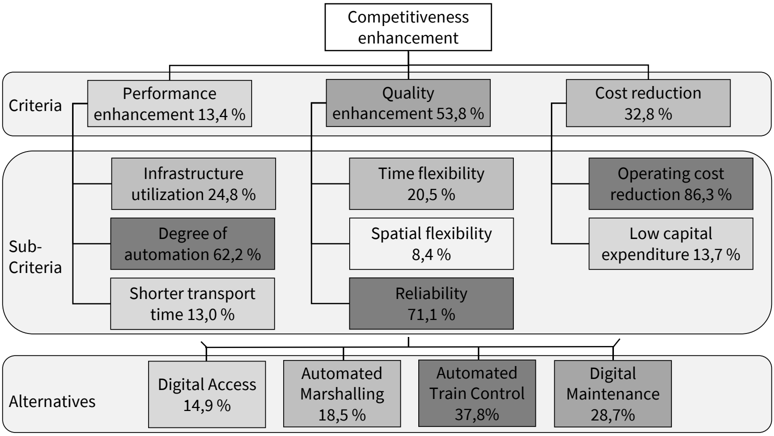

Figure 4: Result representation in the decision hierarchy (own representation according to (Gudehus, 2010; UBA, 2010; Meier, Sender and Voll, 2013; Muschkiet and Ebel, 2013; Sauerbrey and Mahler, 2014; Wannenwetsch, 2014; Breuer and Lieder, 2017; Enning and Pfaff, 2017; Stoll, Schüttert and Nießen, 2017; Schmidt, Enning and Pfaff, 2018; Zapp, 2018; Lutz, 2019; Europäisches Parlament, 2021; Müller, 2021))

Figure 4 shows the entire decision hierarchy and the results of the pairwise comparisons (see 3.2 for details on how the percentages are calculated).

Performing the pairwise comparisons shows that Automated Train Operation has the highest priority (37.8%), closely followed by Digital Maintenance (28.7%). Automated Marshalling (18.5%) and Digital Access (14.9%) have a rather low relevance.

The Consistency Index - i.e., the value indicating whether the experts' assessments are consistent within themselves - is below the recommended value of 10% in the overall result at 6.3% and thus in the optimum range. The sensitivity analysis, also provided by the AHP-OS tool, shows a robust result, i.e., the ATC would lose its first place only if large changes in the ratings were to occur at the decision alternative level. Incidentally, the same is true for the second place of Digital Maintenance. At the sub-criterion level, the model is even more stable; here, the tool sees only one change in the ratings within the realm of possibility. However, this would also only result in Digital Access and Automated Marshaling swapping places.

5 Discussion

This chapter discusses the results of the AHP, addressing the different preferences of the experts. The consensus score given is calculated by the AHP-OS tool and uses the weighted geometric mean aggregation of the experts' judgements (Goepel, 2018).

At the **criteria** level (Table 2), the result of the pairwise comparisons show quality improvement as the most important attribute. It should be noted that the experts are by no means in agreement here, even though the consensus of nearly 54 % is significantly higher than the approx. 33 % for cost reduction. Expert B prefers quality improvement more strongly than expert A prefers cost reduction, which is why the overall results appear clearer than they are.

Table 2: Results matrix for competitiveness

Participant	**Performance enhancement**	**Quality enhancement**	**Cost reduction**
Consensus	13,4 %	53,8 %	32,8 %
Expert A	7,5 %	18,3 %	74,2 %
Expert B	12,2 %	80,4 %	7,4 %

Expert A identified cost reduction as the most important criterion because he describes rail freight as a low-margin business that can offer price advantages to customers with cost reductions in operations and thus make itself more attractive. Expert B argued in favor of quality enhancement, as in his view the mass performance of block train transport, i.e., the bulk of the rail freight business, leaves little room for significant cost savings, but can still make significant gains in the area of service and offer advantages in this way. Support can be found in the literature for both views, both that cost reductions must counteract declining productivity (Doborjginidze, 2005), and that transport quality is a decisive factor in the choice of transport mode (Muschkiet and Ebel, 2013). Both experts agree on the quality enhancement sub-criteria (Table 2). Reliability is the decisive factor here. This is because rail freight transport is inferior to road freight transport in terms of reliability (Schmidt, Enning and Pfaff, 2018), although catch-up potential is still seen here in this context. Flexibility, on the other hand, plays a rather subordinate role in this area. Here, the initial situation is the same (poorer flexibility of rail freight), but road has such an advantage qua natura that an attempt to catch up and the corresponding result would not justify the resource input required for it (Muschkiet and Ebel, 2013).

Table 3: Results matrix regarding quality enhancement

Participant	Time flexibility	Spatial flexibility	Reliability
Consensus	20,5 %	8,4 %	71,1 %
Expert A	28,5 %	6,2 %	65,3 %
Expert B	14,3 %	10,9 %	74,8 %

In the area of **decision alternatives**, the consensus for the strongest decision alternative in percentage terms, Automatic Train Control, is moderate. The ultimately decisive factors here are the sub-criteria reliability and operating cost reduction, which account for just under two-thirds of the overall relevance.

As can be seen in Table 4, the alternatives ATC and Digital Maintenance are practically on a par for the reliability sub-attribute with 0.370 and 0.373 respectively. Here, Expert B argues in favor of ATC, which should enable smoother travel (e.g., through the elimination of signaling systems), especially through the introduction of ETCS, and can thus achieve improvements in punctuality. Expert A favors digital maintenance. Unforeseen disruptions are to be prevented by closer-meshed and more efficient monitoring of the infrastructure and vehicles. Above all, the fact that 50% of all disruptions occur in the area of switches lends weight to this view (Eurailscout, 2021). The fact that Expert B gave digital maintenance a relatively good rating here means that it is still just ahead of ATC overall. The significant difference, however, comes in the reduction of operating costs. Here, both experts grant a high relevance to ATC. While Expert A considers Digital Maintenance to be the most important category, Expert B sees more advantages in ATC. The unanimity with regard to ATC can also be underlined by other sources (Hagenlocher and Wittenbrink, 2015; McKinsey&Company, 2018).

Table 4: Overall results of the decision hierarchy

Criteria	**Sub-Criteria**	**Global Priority**	**Digital Access**	**Automated Marshalling**	**Automated Train Control**	**Digital Maintenance**
Performance enhancement 0,134	Infrastructure utilization 0,248	3,3%	0,427	0,102	0,351	0,120
	Degree of automation 0,622	8,3%	0,249	0,252	0,399	0,100
	Shorter transport time 0,130	1,7%	0,308	0,217	0,377	0,099
Quality enhancement 0,538	Time flexibility 0,205	11,0%	0,198	0,186	0,352	0,264
	Spatial flexibility 0,084	4,5%	0,127	0,151	0,557	0,166
	Reliability 0,711	38,2%	0,130	0,127	0,370	0,373
Cost reduction 0,328	Operating cost reduction 0,863	28,3%	0,060	0,261	0,415	0,264
	Low capital expenditure 0,137	4,5%	0,329	0,163	0,071	0,437
	Sum	1,0	**14,9%**	**18,5%**	**37,8%**	**28,7%**

6 Conclusion, Limitations and Further Research

The overall result indicates that a smooth-running transport process through improved train routing as well as a rail network as free of disruptions as possible through fewer unforeseen failures of switches or trains should be the focus for future digitalization measures in rail freight. Therefore, the digitalization measures are to be prioritized primarily from the category Automated Train Operation and secondarily from the category Digital Maintenance. In addition to prioritizing the measures, it is clear that effective digitalization in rail freight must be holistic (Lotz et al., 2020). However, individual components such as the implementation of ETCS will cost around 32 billion euros, making comprehensive rail digitalization a cost-intensive project (Schmitz, 2021). Expert B mentioned that about 52 billion euros are needed to reach 25% of the modal split for rail freight transport (Schlesiger, 2021). Financing such projects also requires additional policy measures that not only provide the financial resources but also increase investment incentives in rail freight.

Expert A pointed to CO_2 compensation costs as the strongest lever to make rail more competitive with road. In addition to the prioritization of digitalization measures, the present research work has thus also revealed that rail freight transport has a problem regarding transport costs. Operating costs must not be allowed to rise any further, as this would make rail less competitive (Weser-Ems-Wirtschaft, 2021). Thus, a digitalization strategy cannot be considered in isolation from other factors such as implementation costs and operating costs. In addition, potential threats, such as the risk of cyberattacks, should also be considered when introducing digitalization measures, and a comprehensive strategy for the security of digital systems in rail transport should be established. In this way, rail systems can be made not only digital but also secure (European Union, 2019). In conclusion, the research question can be answered as follows: To increase the competitiveness of rail freight transport compared to road freight transport, automated train operation should be prioritized over digital maintenance. However, digitalization per se can only represent one building block for increasing competitiveness (Lotz et al., 2020), and thus a holistic perspective is of particular importance.

The limitations are due to the selected temporal and spatial perspective since this study examines current digitalization measures in Germany. Even if the digitalization measures presented were to be introduced across the board, road freight transport would also continue to develop, which means that increased market shares for rail cannot be guaranteed. Furthermore, freight trains are only economically viable from a distance of over 300 km and for transported goods volumes of 30 - 35 truckloads and above, and therefore a comparison between rail and road is only possible to a limited extent, as a limiting factor in the profitability becomes apparent here (Pfohl, 2018). Another limitation is that only 2 experts participated in the AHP and the customer perspective was not considered. Kinra and Kotzab (2008) highlighted three general limitations of the AHP. The methodology is a quantitative approach that makes it difficult for outsiders to understand individual decisions. In addition, the decisions are, at their core, based on the subjective choices of the experts. Finally, it should be mentioned that the ratio scale of 1 - 9 can represent technical inadequacies (Kinra and Kotzab, 2008).

Future research work could identify further measures that also increase the competitiveness of rail. Here, the focus could be on measures such as the revision of existing regulatory standards, for example regarding CO_2 pricing, or further network expansion, which do not fall directly into the area of digitalization. In this way, further recommendations for action can be made for policymakers by prioritizing the packages of measures as well as individual measures to provide a more targeted overview for increasing the competitiveness of rail freight transport. After all, politics ultimately has an enormous influence on the development of rail freight transport as a whole (VDV, 2015; Enning and Pfaff, 2017). Another way of examining digitalization in rail freight would be to take an even broader look at the concept of digitalization regarding digital transformation. Here it would be of interest whether there is a need in rail freight sector to digitalize not only train operations, but also corporate structures and processes.

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