

Article

Improving Procedures for Maintaining Existing Railway Station Infrastructure in Poland as an Element of the Sustainable European Ecological Transformation

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Abstract: Railways play a key role in sustainable development, being one of the most ecological means of transport. The article discusses the challenges and opportunities related to the maintenance of the railway station infrastructure in Poland, in the context of modern predictive technologies. The Eurail FP3 project, implemented under a European Union grant, focuses on the development of the modern solutions for the maintenance of railway infrastructure, including the possibility of using a modern approach to monitoring the technical condition of buildings in real time, which allows for the prediction of faults and the optimization of the maintenance work. The authors of the article analyze the data obtained from the main manager of the railway infrastructure in Poland regarding the station maintenance procedures and present a new approach for a maintenance procedure, which assumes the inclusion of predictive technologies. Thanks to this, it is possible to optimize the maintenance processes of the station infrastructure, which in the long term will affect the possibility of the current access to data on the condition of buildings in real time and will affect the operating costs related to the maintenance of the station facilities, as well as limiting the negative impact on the environment. The analysis carried out as part of the completed works has also revealed the threats and difficulties related to the costs and technological limitations related to the implementation of the maintenance policy, while indicating the directions of further works to ensure the proper efficiency of the railway infrastructure.

Keywords: predictive maintenance; railway infrastructure; sustainable transport; European Green Deal infrastructure modernization; FP3-IAM4Rail



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1. Introduction

Railways play an important role in the modern world, allowing for the provision of transport possibilities in many sectors of the economy, which is of great importance in the context of the current efforts to reduce greenhouse gas emissions and promote sustainable development systems [1,2]. With the increasing ecological awareness, rail transport is becoming the preferred means of transport and communication due to its lower negative impact on the environment compared to other forms of transport such as cars or planes [3]. This is related to the amount of CO₂ generated per passenger using a given means of transport. Moreover, according to the estimates by the European Environment Agency, rail transport is responsible for only 0.5% of CO₂ emissions in the European Union, while road transport generates as much as 72% of emissions from the transport sector [4]. The growing potential of railways is confirmed by statistical data (Figure 1) indicating the growing popularity of this form of transport from year to year [5] both in Poland [6] and the European Union [7] with a visible post-pandemic recovery of this popularity and a clear upward trend during the years 2021–2023.

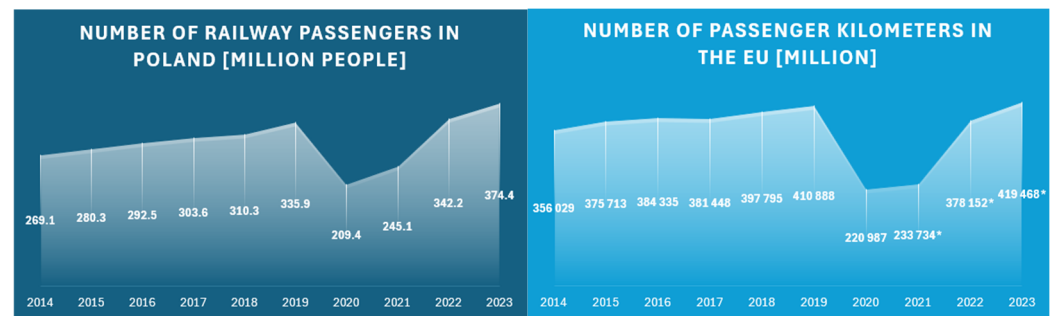


Figure 1. Number of rail passengers in Poland and number of passenger-kilometers in EU countries (own study based on [5,6]), * lack of all data from member states in EU statistics).

The constantly growing popularity of railways requires ensuring the appropriate maintenance activities related to infrastructure that guarantee an appropriate level of reliability and the safety of passengers and allow for offering journeys at appropriate speeds as expected by passengers [8,9].

Unfortunately, due to the not always available and properly maintained railway infrastructure, especially in Eastern European areas, it is not possible to use the potential of railways fully. The international project, FP3-IAM4Rail, co-financed by the European Union, focuses on the issues related to the possibilities offered by railways in the transport sector and the challenges in the design, construction, maintenance, and use of railway infrastructure. The project provides innovative technical requirements, methods, solutions, and services—including technical requirements and standards for the future developments—based on the latest cutting-edge technologies to minimize the asset lifecycle costs and extend the service life while meeting the safety requirements and improving the reliability, availability, and capacity of the railroad system (both infrastructure and rolling stock are addressed) [10].

As part of the work on the project, the authors of the article focus on researching the use of predictive technologies (including Digital Twin (DT)), which enable the real-time monitoring of the technical condition of the infrastructure (in particular the station facilities) and predicting the potential failures. This allows not only the optimization of the maintenance processes, but also the significant reduction in the negative impact on the environment by performing maintenance and repair activities to a degree appropriate for the condition of the element.

One of the main goals of the article is to present a modified procedure for maintaining the station facilities, which was created based on the work carried out as part of the research in Work Package 14 (WP14) of the FP3-IAM4Rail Project on the analysis of the possibilities of using modern technologies for improving the reliability, safety, and efficiency of the management of the key infrastructure facilities [11], which required, among other things, the analysis and modification of the existing railway infrastructure maintenance solutions.

The modified maintenance procedure for the railway station facilities presented in the article aims to strengthen the aspects of sustainable development, such as optimizing the use of resources, minimizing energy losses, and promoting the long-term durability of buildings. By including the use of predictive technologies in the procedure, it is possible to manage the life cycle of railway stations more effectively, which brings visible benefits in both environmental and economic aspects when used [12,13].

2. Maintaining Railway Infrastructure in Poland and Developed Countries

Ensuring the efficiency, safety, and reliability of the rail transport system requires the proper maintenance of the entire, complex system of technical infrastructure [14,15]. Figure 2 presents the elements of the system that affect the way it functions. From the perspective of infrastructure maintenance, it should be noted that each element of the facility requires a separate approach to the method and possibility of its proper maintenance, and

is also associated with the need to meet the other statutory obligations in the field of inspections.

Linear infrastructure	Point infrastructure	Signaling and safety systems	Energy infrastructure	Other supporting elements
• Railway tracks: consists of rails, sleepers, ballast, and fasteners that create a physical path for trains. • Switches: places where rail tracks branch off, allowing trains to change tracks. • Engineering structures: bridges, tunnels, embankments, slopes, and other structures that help maintain track stability.	• Railway stations: buildings used for passenger service, with commercial and service functions such as ticket offices, waiting rooms, and platforms. • Platforms: places where passengers board and alight from trains. • Freight stations and sidings: infrastructure dedicated to handling and loading/unloading freight. • Locomotive sheds and workshops: places where locomotives and wagons are stored, maintained and repaired.	• Semaphores: lighting and mechanical systems used to control train movements. • Safety systems: automatic systems to prevent collisions, such as the Automatic Train Stop (ATS) or the European Train Control System (ETCS). • Telecommunications systems: networks enabling communication between operational staff, stations and trains.	• Traction lines: systems of cables that supply electricity to electric trains. • Traction substations: installations responsible for transforming and supplying electricity to the traction network.	• Drainage systems: channels and gutters that drain water from the tracks. • Monitoring and management systems: technologies such as Rail Traffic Management Systems (RTMS) and systems for monitoring the technical condition of the infrastructure (e.g. vibration, pressure, deformation sensors).

Figure 2. Elements of railway infrastructure. Own study based on [16–20].

Each of the mentioned infrastructure groups in Figure 2 requires a different approach to maintaining efficiency, adapted to its specificity [21], because all the systems and elements together affect the safety of rail transport [19]. A significant problem on the Polish market is that the maintenance of each of the components listed in Figure 2 is formally the responsibility of a different entity, which uses its own procedures and principles in the field of maintenance policy. This often leads to conflict situations, where the actions taken are not consistent, and as a result, the entire system does not work properly.

In the literature, there are various approaches to maintaining the efficiency [22–24] of the infrastructure, which can be used to verify the condition of the railway station facilities, the most common of which are reactive, implementation, preventive, and predictive.

A **reactive** strategy is the basic and most frequently represented strategy in the maintenance of construction facilities [25], including buildings. The surveys conducted by the authors during the research in the period 2021–2022 [26,27], which were addressed to entities professionally involved in real estate management, including the internal units of the corporations responsible for the technical maintenance of the construction facilities using the resources of a given corporation, allowed the authors to determine the share of the represented maintenance approaches. The survey sample ultimately included 68 entities, the size of which, depending on the number and size of the managed properties, can most often be described as an average. As a result of the research, it can be stated that it is the reactive approach that is the most frequently used approach in maintenance—less than 71% of the entities indicated the reactive strategy as the basic and only one in the maintenance of the construction facilities. This state of affairs seems to result—as the study shows—from the relatively and seemingly low maintenance costs. The reactive approach is based on the occurrence of a reaction only as a result of noticeable and already occurring events that require a reaction. In fact, the reactive approach does not generate high costs, but only in a situation where there is no event that forces a reaction, which is only seemingly a favorable circumstance. The risk of technical problems that may lead to the necessity of decommissioning the facility is much more dangerous than the calculation of the maintenance costs and possible reaction, especially in the case of facilities that are a component of the key communication system. In such a situation, the cost calculation no longer results only and exclusively from the maintenance and necessary reactions, but may be related to the possible consequences of the existing restrictions in use [28].

The implementation approach [29,30] is based on a system of planned and preventive repairs and constitutes a certain evolution towards preventive approaches, i.e., those in which the occurrence of an unfavorable event causing restrictions in the functioning of the system is reduced. The implementation approach is based on establishing a fixed schedule for performing specific maintenance and repair activities, which should ensure the full, uninterrupted serviceability of the object that is part of the system, in particular by reducing the occurrence of failures resulting from natural and predictable factors (incidents may be an exception). The weak point of the implementation approach is the high and basically fixed cost of activities occurring at the operational stage in connection with the implementation of the established schedule. In addition, the implementation approach is based on normative durability, which is not always a good representative of the actual condition of the object's elements; therefore, the activities undertaken based on the established schedule may be significantly ahead of the actual need. Nevertheless, in this approach, the occurrence of failures is significantly reduced, although there is no full guarantee that these phenomena do not occur at all.

The preventive approach [31,32] is classified as a proactive approach. In the preventive approach, the activities undertaken result from the cyclical supervision of the technical condition through inspections and reviews. Depending on the interval of inspections and reviews, it is possible to identify the actual need for a response, in particular based on the symptoms that herald it—if any. However, the preventive approach does not exclude the occurrence of incidents, the effects of which reduce the usability of the facility.

The predictive approach [33–36] concerns the adoption of a maintenance strategy that involves monitoring the technical condition of infrastructure in real time using the data collected using sensors and advanced technologies, such as the Internet of Things (IoT) and Big Data. The predictive approach is an evolution of the preventive approach, where instead of or in addition to inspections and controls, technological development and automation are used. The predictive approach assumes active monitoring in order to determine the condition of the facility and building forecasts of changes in the technical condition and related potential unfavorable events causing restrictions on the use of the facility, so as to prevent them. By implementing various monitoring techniques (e.g., visual, sensory), it is assumed that an automated data acquisition and status information device will be used. Furthermore, by using the inference model, it is possible to support actions by selecting them and taking them in advance, so that the result of the actions will eliminate the disruptions in use, without reducing the usability and while limiting the costs of the actions.

Focusing on the railway stations, it should be noted that in Europe, taking into account the pursuit of green ecological transformation, infrastructure management plays an important role in achieving the goals related to reducing CO₂ emissions and promoting sustainable development [37]. Western European countries such as Germany, France, and the Netherlands have been introducing modern maintenance procedures for many years, which are consistent with the assumptions of the European Green Deal [38,39]. An example are the solutions used by Deutsche Bahn, which consist of the integration of predictive methods and monitoring systems based on technologies such as DT, which allows for predicting faults and optimizing the life cycle of infrastructure. In Germany, advanced energy management systems have also been used, allowing for the optimization of the energy consumption in the station facilities, reducing their carbon footprint [40]. In turn, in France, SNCF is conducting an extensive program of modernization of the railway stations, taking into account the sustainable development procedures. It includes, among others, the installation of energy recovery systems, the automatic monitoring of resource consumption and the improvement of the energy efficiency of buildings. These procedures are often supported by real-time data analysis, which allows for the dynamic adjustment of the maintenance schedules according to the actual technical condition of the infrastructure [41].

In the United States, the extensive rail network and its intensive use for freight transport, in particular, pose additional challenges for the infrastructure maintenance. The rail

operators are implementing condition monitoring systems, such as vibration, temperature, stress, and geometry sensors, which provide real-time data [42,43]. The use of data analysis and machine learning algorithms allows for the identification of wear patterns and potential failure points, which allows for the planning of the maintenance interventions before problems occur. An example of the technology used in the US is Ultrasonic Broken Rail Detection (UBRD), which enables the continuous monitoring of rails for cracks and internal defects [44]. This allows operators to respond quickly to the detected irregularities, minimizing the risk of derailments and other serious incidents. In addition, the integration of Global Positioning Systems (GPSs) with monitoring technologies such as the Automated Track Inspection Program (ATIP) [45] enables the precise determination of location and the tracking of the condition of individual track segments.

In Japan, where rail plays a key role in the passenger transport, predictive maintenance is an integral part of the infrastructure management strategy. Japan East Railways (JR East) uses advanced monitoring systems such as Fiber Bragg Grating (FBG) sensors [46] that measure the stress and deformation in the infrastructure components [47]. These data are analyzed using artificial intelligence, which allows for component wear prediction and maintenance planning in a way that minimizes the disruption to traffic [48].

In addition, Japan is pioneering the use of robotics in the rail infrastructure maintenance [49]. Inspection robots equipped with cameras and sensors are used to examine hard-to-reach areas, such as bridge undercarriages or tunnels. Integrating these technologies with predictive systems increases the precision of diagnoses and the effectiveness of preventive measures.

In Poland, the situation is more diverse, but there is also a visible increase in the interest in the modern monitoring and maintenance technologies, but mainly the traditional, preventive maintenance methods are used in practice, which limits the possibility of the full optimization of the maintenance processes and reducing the operating costs. A change in approach is observed in this area related to the use of European funds promoting agriculture, which forces the use of approaches that reduce the resource consumption and carbon dioxide emissions. For this purpose, large research projects are being carried out, of which Poland is a part, such as Eurail FP3, within which it will be possible to develop solutions that will allow for the planning and implementing of innovative solutions supporting sustainable development.

3. Existing Maintenance Procedures for the Railway Station Facilities in Poland

As part of the research aimed at developing solutions enabling the efficient and at the same time sustainable supervision of the condition of railway infrastructure—railway station facilities—data were obtained from the largest entity servicing the railway infrastructure in Poland in the scope of infrastructure maintenance procedures. The PKP company manages nearly two thousand railway stations [50], of which 581 are active railway station facilities [51] (as of 31 August 2024). The facilities include both large transport hubs, such as Warszawa Centralna, Kraków Główny, or Gdańsk Główny, as well as smaller facilities serving local traffic. Many of these stations are currently undergoing a modernization process, which aims not only to improve their technical condition, but also to adapt them to the modern passenger service standards, which gives the potential for the implementation of modern management methods based on the idea of sustainable development [52].

Extensive documentation of the processes shows that the maintenance activities are carried out based on the established maintenance and inspection schedules. The data obtained in this way are used in the subsequent stages of preparing renovation plans or force the implementation of ad hoc actions in the event of determining the necessity of their implementation. These data cover various aspects of station infrastructure management, including in particular the following:

- Type of inspection is indicated: the data include both visual inspections and inspections using measuring tools such as thermal imaging, and devices for testing vibrations, humidity, or the level of wear and tear of building materials.

- The necessary scope of activities to be performed as part of a given review or control is indicated. The procedures indicate what elements should be verified as part of a given control and define the method of assessment, together with information on where and how the result of the activity performed as part of the review or control should be recorded.
- The frequency of inspection is indicated. Depending on the type of verification activity performed, it is indicated with what frequency a given control activity should be performed. In the case of periodic inspections required by the law, the frequency results directly from the applicable regulations, which in the case of railway station buildings requires the following inspections:
 - annual (for (a) building elements, structures, and installations exposed to harmful atmospheric influences and the destructive effects of the factors occurring during the use of the facility, (b) installations and devices for environmental protection, as well as (c) gas installations and chimney flues (smoke, exhaust, and ventilation));
 - 5 years, covering building elements, structures, and installations exposed to harmful atmospheric influences and the destructive effects of the factors occurring during the use of the facility:
 - the esthetics of the building and its surroundings;
 - installations and devices for environmental protection;
 - gas installations and chimney flues;
 - electrical and lightning protection installations.
 - semi-annual (for large-scale facilities with a specific building area, i.e., exceeding 2000 m², or roof area exceeding 1000 m²);
 - annually in the case of electrical installations, every five years for structural elements, such as foundations and roofs, and every few months for critical installations, such as fire protection systems.

The procedural data obtained during the work made it possible to illustrate the methods used to carry out the current assessment of the technical condition of the station facilities (Figure 3).

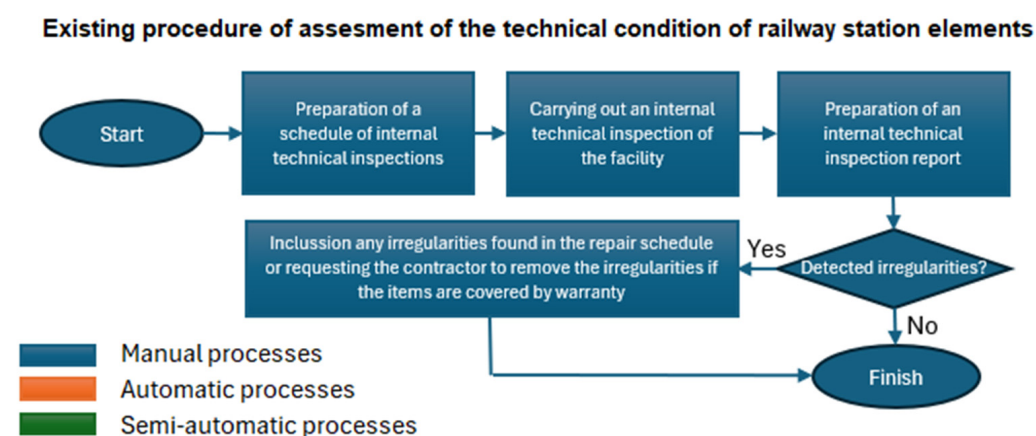


Figure 3. Diagram of the existing procedure of maintenance of technical condition of railway station elements in Poland (own work).

The data obtained allowed the summarization that the current railway station maintenance procedures are based on the traditional preventive methods, i.e., preventive maintenance, which consists of regular inspections and maintenance activities.

Attention should be paid to the necessity for manual data acquisition and the lack of process automation and data exchange platforms enabling access to the current condition of the station facilities.

In addition, it is stated that the predictive methods based on the real-time monitoring of technical conditions are not used, which is understandable considering the condition of the railway station infrastructure, which includes buildings of various types, sizes, and various technical conditions. Figure 4 presents examples of the railway station buildings in Poland with different technical conditions.



Figure 4. Different technical conditions and types of railway station buildings found in Poland in Biskupice, Jarocin, Środa Wielkopolska, Krotoszyn (own research work).

It is clearly visible that the significant difference between Poland and much of Western Europe in terms of the railway infrastructure maintenance lies in the level of the modernization and adoption of predictive maintenance technologies. In Poland, the maintenance practices for the railway infrastructure, including the station facilities, rely on the traditional, preventive maintenance approaches, which involve scheduled inspections and repairs based on fixed intervals. This approach, while providing a structured schedule, may lead to the over maintenance or delayed response to the emerging issues, as it does not always reflect the actual, real-time condition of the infrastructure, which is one of the reasons why many different train stations are in different technical conditions.

4. SWOT Analysis of the Maintenance of the Railway Station Facilities in Poland

SWOT analysis [53,54] is a strategic analysis tool that allows for the assessment of the internal and external factors affecting the functioning of an organization, project, or infrastructure [55]. This method was developed in the 1960s by researchers from Harvard Business School and is widely used in various economic fields, such as management, marketing, strategic planning, as well as infrastructure engineering and maintenance. SWOT analysis allows for a systematic assessment of both strengths and weaknesses (internal factors), as well as opportunities and threats (external factors). This allows for understanding the strategic situation of the analyzed area and identifying the key areas requiring intervention or further research [56].

As part of the research and analytical work, a broader analysis of the existing solutions in the field of station maintenance procedures was carried out, which indicated the potential

for their improvement. For this purpose, as part of improving the existing process approach currently in operation, a strategic SWOT analysis was carried out (Figure 5). The analysis included the existing state of the station infrastructure determined on the basis of study visits. They allowed for the identification of new possibilities not included in the previous process approach.

SWOT	Strengths	Existing regular maintenance schedules Experience in infrastructure management EU horizontal priorities in rail Extended station infrastructure Modernisation of facilities EU horizontal priorities in rail	Threats	Costs of implementing technology Technological limitations of older buildings Changing laws and regulations Lack of qualified staff Current geopolitical situation
	Opportunities	Introduction of predictive methods Funding from EU funds Increasing energy efficiency Data integration and digital management	Weaknesses	Lack of predictive methods Diverse technical condition of facilities Budgetary and formal-legal constraints Frequency of inspections

Figure 5. SWOT analysis of the maintenance of railway station facilities based on existing maintenance procedures.

Below is a detailed discussion of the elements indicated in the Figure.

Strengths:

- Extensive station infrastructure: the management company oversees nearly 2000 railway stations, which provides ample opportunities to implement unified maintenance procedures and management on a large scale.
- Existing regular maintenance schedules: regular technical inspections, including annual, semi-annual, and five-yearly inspections, allow for the detection of problems and prevent the occurrence of major failures.
- Experience in infrastructure management: the management company has many years of experience in managing facilities of various sizes and technical conditions, which allows for the effective application of the currently applicable maintenance procedures and provides the potential for their improvement.
- Modernization of facilities: the currently implemented modernization projects include the reconstruction and modernization of many station facilities, which allows for the improvement of the technical condition of buildings and their adaptation to the modern standards of sustainable development.
- EU horizontal priorities in railways: promoting rail transport in the EU provides the potential for obtaining financing for the activities related to the maintenance of the facilities, including the integration of the systems supporting the modern infrastructure management techniques.

Weaknesses:

- Lack of use of predictive methods: the current procedures are based mainly on preventive methods, which do not allow for the full use of the modern monitoring and prediction technologies used in Western European countries.
- Diverse technical condition of the facilities: Railway station buildings differ in age and technical condition, which makes it difficult to simultaneously implement unified maintenance procedures and modern technologies on a broad scale. Historic facilities are particularly problematic in this respect, where the possibility of conducting new technical infrastructure is difficult or completely limited.
- Budgetary and formal-legal constraints: The high costs of the modernization and maintenance of such extensive infrastructure, especially older and historic facilities, limit the possibilities of rapid implementation of new technologies, which, combined with the specific formal-legal reality in Poland, makes it difficult to implement the modern maintenance methods. In particular, the legal conditions regarding the method of spending public funds affect the duration of the projects in the field of the renovation and modernization of railway infrastructure.

- Inspection frequency: due to the introduction of two inspection schedules, some inspections of the technical condition of the station facilities may be carried out more frequently than necessary, which generates additional operating costs.

Opportunities:

- Introduction of predictive methods: The implementation of modern technologies such as the IoT, Big Data elements, and monitoring sensors can optimize the maintenance processes, potentially reducing the operational costs in the field of maintenance. Additionally, it is possible to improve the safety of the station users and increase the durability of the station infrastructure.
- Financing from EU funds: the possibility of using European funds, such as Horizon Europe and projects such as Eurail FP3, can accelerate the modernization of the stations and the implementation of the maintenance technologies that are consistent with the idea of sustainable development and promoted under the European Green Deal.
- Increasing the energy efficiency: the introduction of energy management systems, intelligent buildings, and renewable technologies (e.g., solar panels, energy recovery systems, the supervision of energy receivers) will reduce the consumption of natural resources and CO₂ emissions.
- Data integration and digital management: the possibility of building an integrated database of rail infrastructure, enabling more effective management and maintenance of the facilities at the national level can contribute to increased access to information on the current condition of the station infrastructure.

Threats:

- Costs of implementing the technology: the high costs associated with installing the modern monitoring systems and predictive technologies may constitute a barrier to the rapid modernization of the stations and their implementation.
- Technological limitations of older buildings: the difficulties in integrating the modern systems with the infrastructure of older, often historic buildings may delay the modernization and lead to a division into modern facilities and facilities requiring further investment (significant modernization outlays).
- Changing regulations and laws: dynamically changing the regulations on environmental protection and infrastructure management may force frequent changes in the approach of managers and persons responsible for maintaining the station infrastructure in line with the modernization needs.
- Lack of qualified staff: the implementation of the new technologies requires the training of staff, and the lack of suitably qualified staff will delay the implementation of the modern solutions.
- Current geopolitical situation: The armed conflict that is ongoing beyond Poland's eastern border may pose a threat to the territorial integrity of Poland and the EU. In the event of its escalation, the modernization of the stations in accordance with the objectives of the Green European Deal may fade into the background.

At the same time, the identified opportunities related to the possibility of implementing predictive technologies and the availability of EU funds under the Horizon Europe programs carry the greatest transformation potential. The introduction of real-time monitoring systems and Big Data elements can significantly improve the efficiency of the maintenance activities, reduce the operating costs, and increase the durability of the infrastructure. IoT technology and monitoring sensors can also contribute to increasing the passenger safety and reducing the risk of failures. Moreover, the integration of technical data in an integrated database of station infrastructure could improve the management at the national level, which would enable the better monitoring of the current technical condition of the facilities and the optimization of the maintenance activities. Such solutions would be in line with the priorities of the European Green Deal, which promotes sustainable transport and energy efficiency, as well as with the procedures used in other European Union countries [57]. However, a change in approach requires taking into account a new

approach in the maintenance procedures and algorithms, which will require modification in this respect.

5. Assessment of the Technical Condition of the Railway Station Elements with the Use of a Proposed Operational Diagram of the Maintenance Procedure

Based on the results of the analyses performed, including the SWOT analysis, the authors propose an original approach to the process of assessing the technical condition of the railway station elements, which will be based on the creation of a database of the technical condition of the railway station building elements. In order to fully understand the proposed approach, the way the database functions is explained at the beginning (Figure 6).

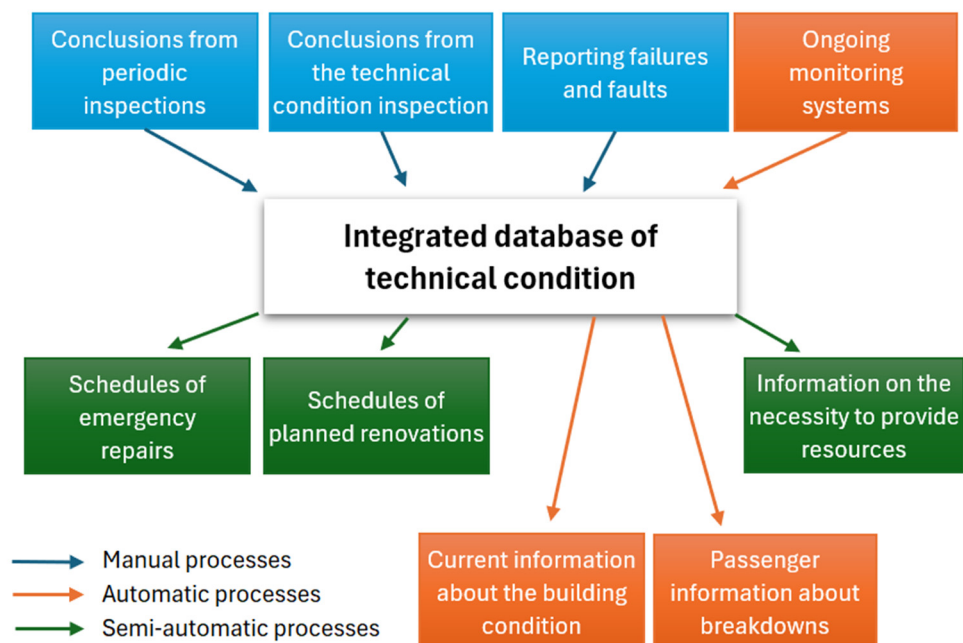


Figure 6. Diagram of the functioning of the database of technical conditions (own work).

The database would enable the supervision of the station infrastructure and would indicate the current technical condition of the station elements, which would facilitate sustainable repair and maintenance management. This would also allow, in the long term, the acquisition of data on the technical condition, as well as the maintenance and repair activities undertaken in connection with this and their results, to build a case database. The case database, as an important element of inference from cases, would enable decision making, including in advance regarding the need to conduct maintenance and repair works.

The stored data include the results of inspections and technical reviews conducted in a form enabling remote access to them in the scope of the following:

- Reviews resulting from the provisions of the construction law;
- Technical condition reviews as part of the company's procedures (technical condition checks);
- Emergency reports and damage to infrastructure;
- Data from current monitoring indicate the condition of the facility.

Based on the above, it would be possible to prepare repair plans and renovation schedules in an automated manner, and after expanding the database with cost estimate data, it would be possible to estimate the values necessary to carry out the renovations. Access to the data on the technical condition of the facilities would be continuous, which in the event of the need to provide information on the failures and exclusions of the elements/parts of the station would enable the immediate automatic notification of the interested parties.

Ultimately, the database constituting an essential element of the proposed procedure should be dynamic and integrated with the real-time monitoring systems to enable the automatic updates of the technical data. The system should also enable the generation of reports and analyses for infrastructure life cycle management, which will allow for increased maintenance efficiency and the minimization of the operating costs and environmental impact. The key issue from the maintenance and operation perspective of the proposed solution is the method of delivering the input data to the database. Below (Figure 7) is an operational diagram of the maintenance procedure presented, with particular emphasis on the method of collecting and placing data in the database, considering the conclusions from the analyses conducted so far.

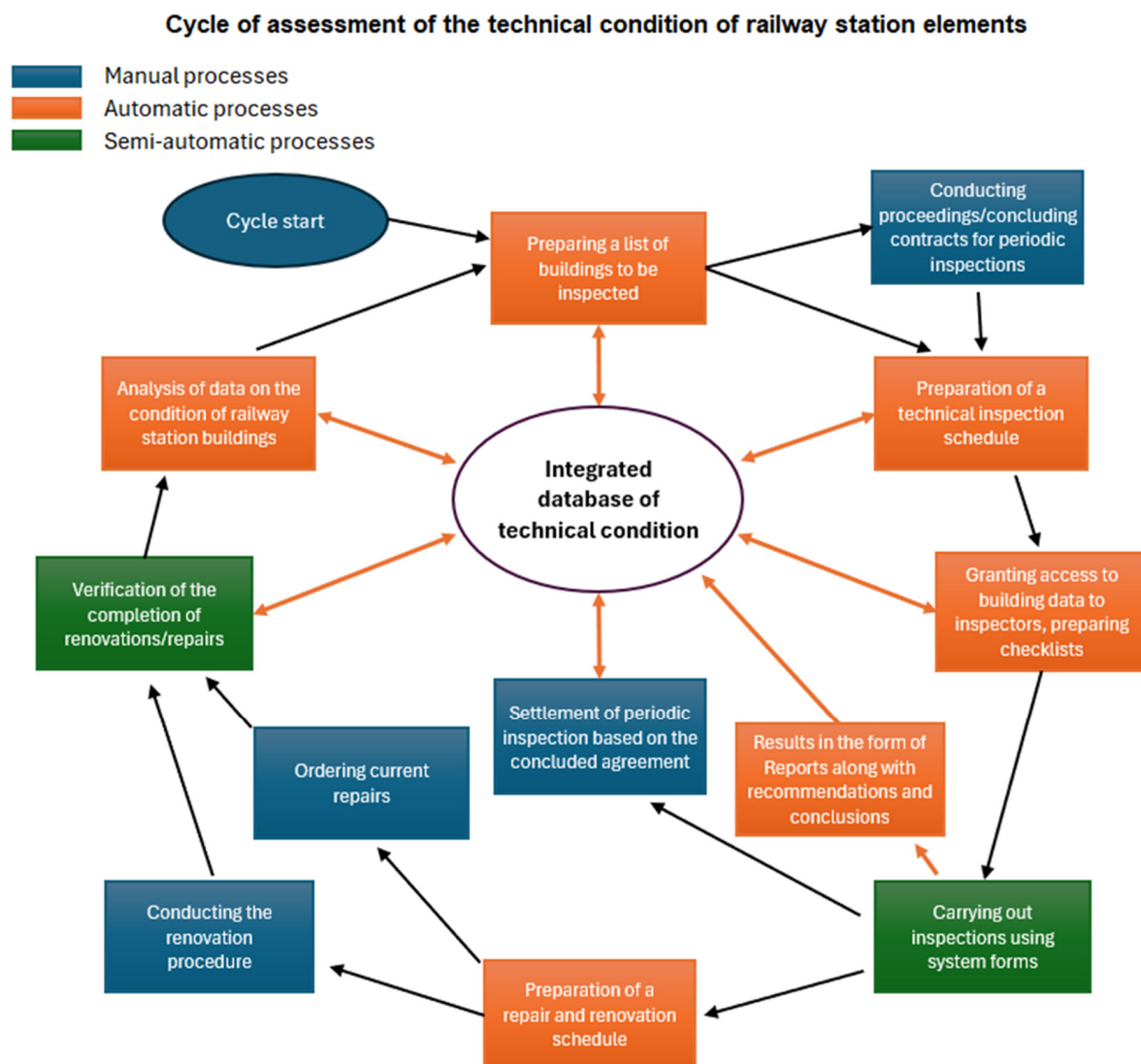


Figure 7. Proposed operational diagram of the maintenance procedure (own work).

Based on the analysis conducted and observations of the current state of the railway stations, it is evident that the existing procedures have limited effectiveness not only in the maintenance activities carried out but also in the inspections themselves. Frequently, the results of these inspections do not provide a sufficient basis for taking proactive measures to prevent events that limit usability. The current approach to maintaining the station buildings can be characterized as reactive and preventive; however, the preventive aspect is not fully realized. Despite formulating post-inspection recommendations, economic

reasons often lead to the implementation of only those measures that address the issues already causing significant limitations.

The proposed solution to this identified problem is a data collection cycle based on a centralized database, which would receive additional data from the monitoring systems (Figure 6). Simultaneously, the proposed procedure (Figure 7) enables the automation of certain tasks that were previously performed manually—particularly activities related to preparing the facilities for technical condition assessments, developing detailed inspection plans, and, based on inspection results, planning renovations and conducting analyses of the current state of the buildings.

Moreover, using the data collected in this manner makes it possible to plan the maintenance and repair activities based on real and current data, which can be accessed directly. This will have a significant impact on the effectiveness of technical condition inspections, and the repair and maintenance plans will be optimized in terms of their validity. This will also have a considerable effect on the costs and resources, including the environmental resources, associated with better resource management.

5.1. Challenges and Barriers

The implementation of the proposed procedure, which considers the predictive approach in the maintenance of the railway station infrastructure, brings with it a number of challenges that may delay or limit the full use of the potential of the proposed solution. One of the key challenges is the potential financial constraints. The full use of the procedure requires the use of monitoring systems, the implementation of which in the existing facilities, especially in the case of older infrastructure that requires adaptation, is expensive.

The second challenge is the technological constraints. Old station buildings, often of great historical importance, are difficult to be adapted [58,59] to the modern monitoring systems. The installation of sensors often requires interference in the structure of the building, which can be problematic from the point of view of the conservation regulations. In addition, many of the station buildings have recently undergone modernization processes, which did not provide the installation of additional monitoring systems related to maintenance management. This may additionally limit the possibilities of using the proposed approach on a full scale.

Organizational challenges also play an important role. The implementation of the modern technologies requires a change in the approach to infrastructure management and training of the staff responsible for maintenance and upkeep. The process of integrating the new technologies with the existing operational procedures in a large enterprise in such a specific industry can be difficult and requires not only providing the appropriate resources, but also changes in the organizational culture.

In practice, overcoming these challenges requires a strategic approach that combines technological innovation with the effective use of the available financial resources.

One way to overcome these limitations is to gradually implement predictive maintenance solutions. Instead of the expensive modernization of the entire infrastructure at once, a phased approach can be used, focusing on the most critical elements of the rail network. This allows for spreading the costs over time and the gradual implementation of the new technologies [13]. In the case of older buildings, often of historical importance, the technological limitations can be overcome by using non-invasive monitoring technologies. Wireless IoT sensors can be installed without interfering with the building structure, allowing for monitoring the key technical parameters in real time without compromising the integrity of the facility [35].

The financing of modernization can be supported also by EU funds for infrastructure development and sustainable transport, such as the Connecting Europe Facility (CEF) [60] or EU structural funds (IAM4RAIL).

The information provided by the rail infrastructure managers in Europe shows that the implementation of the new technologies, also during the renovation and investment

projects in the existing station infrastructure, can be effective, and the effects are visible to passengers:

- Network Rail has implemented the Digital Railway program, which includes the modernization of the rail infrastructure through the implementation of digital technologies and predictive maintenance. Thanks to the use of advanced monitoring systems, it has been possible to improve the operational reliability and efficiency [61].
- The German rail infrastructure manager, DB Netz AG, draws attention to the possibilities offered by modern systems and the integration of predictive maintenance. By integrating the modern monitoring systems (digital maintenance) with the existing infrastructure, it has been possible to significantly improve the maintenance processes [62].

Moreover, the current shift towards railways and the growing popularity of targeted funds for modernization create favorable conditions not only for considering the possibility of implementing automated solutions, but also for the installation of the necessary infrastructure during the modernization works on the station facilities.

5.2. Long-Term Implications of Implementing the Predictive Maintenance Approach for the Railway Station Infrastructure

The long-term implications of implementing the predictive maintenance procedures for the railway station infrastructure are significant, especially in terms of reducing the operating costs and increasing the sustainability in the transport sector across Europe. By moving from traditional maintenance strategies to predictive models, the rail operators can predict the potential failures before they occur, minimizing unplanned downtime and avoiding costly repairs [35,60]. This proactive approach allows the maintenance activities to be planned based on the actual condition of the infrastructure components rather than on fixed intervals, leading to the efficient use of resources and significant cost savings in the long term. Furthermore, predictive maintenance significantly contributes to environmental sustainability by reducing the waste resulting from unnecessary or premature maintenance activities (e.g., component replacement) and optimizing the energy consumption related to the maintenance activities [13]. Reducing the material consumption and energy demand is in line with the objectives of the European Green Deal, which promotes decarbonization and resource efficiency in the transport sector [63]. In the long term, the adoption of the predictive maintenance procedures promotes a reliable and efficient rail network, encouraging a modal shift from road to rail. This shift enhances the environmental benefits by further reducing the total greenhouse gas emissions, thus contributing to the achievement of the objectives set by the European Commission for the environment and sustainable development of Europe.

The implementation of the proposed maintenance strategies not only increases the operational efficiency and safety of rail services, but also positions the rail sector as a leader in the sustainable development practices. As European countries continue to invest in smart infrastructure, the integration of the predictive maintenance procedures will play a key role in the modernization of the rail system, ensuring its competitiveness and supporting the transition towards a more sustainable and environmentally friendly transport network.

6. Summary and Conclusions

The article discusses the challenges and opportunities related to maintaining the railway station infrastructure in Poland in the context of ecological transformation and the implementation of the modern predictive technologies. The railways, as a key element of sustainable transport, play an important role in reducing CO₂ emissions, which makes the optimization of its infrastructure management one of the priorities within the European Green Deal. The SWOT analysis conducted as part of the work showed that the modernization and implementation of the new technologies, such as the real-time monitoring of the technical condition of the facilities, has significant potential to improve the maintenance

processes, which may reduce the operating costs and increase the durability of the railway station infrastructure.

As part of the research, the authors proposed a cycle for assessing the technical condition of the railway station facilities based on the access to an integrated database of technical condition, which allowed for the modification of the existing regulations regarding the method of performing the technical inspections of the railway station facilities. The access to the database will enable the real-time monitoring of the infrastructure life cycle and will introduce the possibility of planning the maintenance and repair activities in a manner adapted to the current technical condition of a given facility. Thanks to the proposed approach, it will be possible not only to better manage the resources, which will consequently contribute to reducing CO₂ emissions, which is consistent with the practices and idea of sustainable development. As part of the further work, and also as part of the Eurail FP3 project, the authors plan to implement and test solutions as part of the pilot activities in the facilities in Poland, which will enable the application and testing of the approach described in the article in practice.

The final full use of the potential of the proposed solutions is associated with the necessary financial and technological involvement, especially in the context of integrating the modern monitoring systems with the existing infrastructure. Researchers believe that implementing these solutions based on the idea of predictive maintenance will bring visible benefits to the entire railway sector in Poland and throughout Europe in the long term.

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