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Implementing Predictive Maintenance Strategy for Infrastructure in the ECRL Project Operation Phase

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Abstract

East Coast Rail Link (ECRL) project is one of the most recent railway project in Malaysia that is on the verge of approaching its operation phase in 2027. Revolving solely around traditional maintenance approaches and absence of predictive maintenance (PdM) approach within its current infrastructure maintenance strategy is a missed opportunity to potentially address the short daily maintenance interval and overcome unforeseen obstacles to the project's long term viability. Hence. this paper addresses the potential of infrastructure maintenance strategy based on PdM implementation in the project's operation phase. It synthesized various past studies regarding PdM, as semi-structured interviews comprising of multiple sections were utilised for gaining the insights and views of technically experienced individuals within the project. Results showed partcipants' understanding and high regards towards PdM's technology and capability, addressing its potential of implementation based on the aspects of ECRL Project. However, several barriers that constraint its adoption were highlighted intensively by each participant such as skill gaps, organizational readiness varies and multinational coordination challenge. Ultimately, the majority agreed on the need of investment and resource commitment from the top leadership on addressing these barriers.

1. Introduction

A structured railway infrastructure maintenance strategy is essential for ensuring system reliability, safety, and cost efficiency. This involves managing key assets like tracks, bridges, tunnels, and power systems through preventive and corrective maintenance (Lidén, 2015; Smith-Wong, 2024). With rail networks growing in complexity and demand, consistent maintenance helps reduce malfunctions and downtime while improving service quality (de Bruin et al., 2017; Vatn et al., 2019), in which the East Coast Rail Link (ECRL) Project is trying to achieve. Being one of the main mega projects in Malaysia, which Malaysia Rail Link Sdn. Bhd. (MRLSB) and China Communications Construction Company (CCCC), the 665 km railway project, currently lead aims to connect the east and west coasts of Malaysia while establishing a joint venture for operations and maintenance (Bernama, 2024). The structure of ECRL infrastructure maintenance plan aims to revolve around traditional maintenance approaches such as preventive and corrective measures, in the form of time-based scheduling and components replacement (CCCC, 2022).

Although still emerging in Malaysia, predictive maintenance (PdM) is gaining traction as a key strategy for infrastructure management. PdM seeks to forecast when an item is likely to break and choose which repair task should be carried out in order on achieving maintenance cost efficiency (Keizer *et al.*, 2017). The utilization of real-time data analytics provides an innovative approach to tackle emerging problems and initiate the proper preventative step before it results to significant interruptions (Yan et al., 2017; Griffiths, 2022). For instance, the implementation stages of Condition-Based Monitoring (CBM) as part of PdM approach for Kereta Api Tanah Melayu (KTMB) Electric Multiple Unit (EMU), in which reliability trend has been assessed from year 2008 to 2014 is highlighted in both Figure 1 and Figure 2 respectively. The progressive growth in actual dependability than the targeted values indicates strong enhancement in maintenance plan and execution, which are closely tied to the implementation of better data systems and tooling in the form of CBM. It aligns with Alaswad & Xiang (2016) in their findings, which highlights PdM's capability in the reducing unnecessary maintenance and lead to asset reliability improvement through minimization of risks associated with preventive measures .

Despite PdM's proven capability in similar railway profile in the form of KTMB's inter region railway, the absence of PdM approach within the current ECRL infrastructure maintenance plan tend to remain a question, especially considering that PdM has the capability on addressing the short maintenance interval and long-term viability of maintenance approach of the project. Hence, this study is proposed to investigate the factors towards the implementation of PdM within railway projects. Next, to verify the barriers that constraints PdM adoption in managing the railway infrastructure of the ECRL Project. Then, to determine ways on overcoming the barriers that hinder PdM implementation within the infrastructure maintenance strategy of the ECRL Project. In general, the research aims to bridge the gaps in existing maintenance practices considered for the ECRL operation phase by informing the industry practitioners of the factors, barriers and ways on overcoming them that could strategically shift the perception towards PdM implementation in the future.

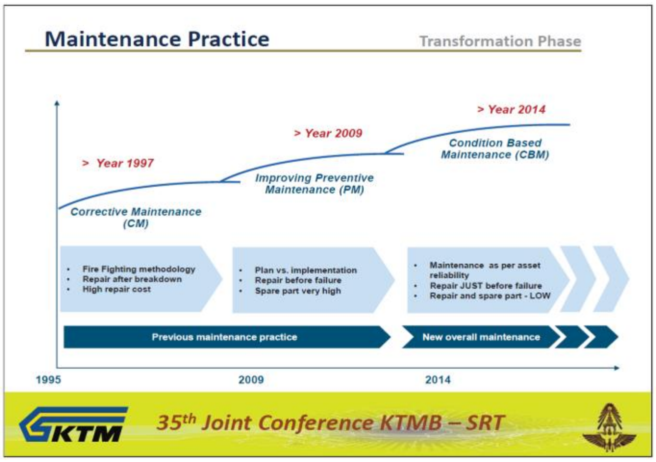

Fig. 1 KTMB's EMU overall maintenance practice stages (Jumain, 2014).

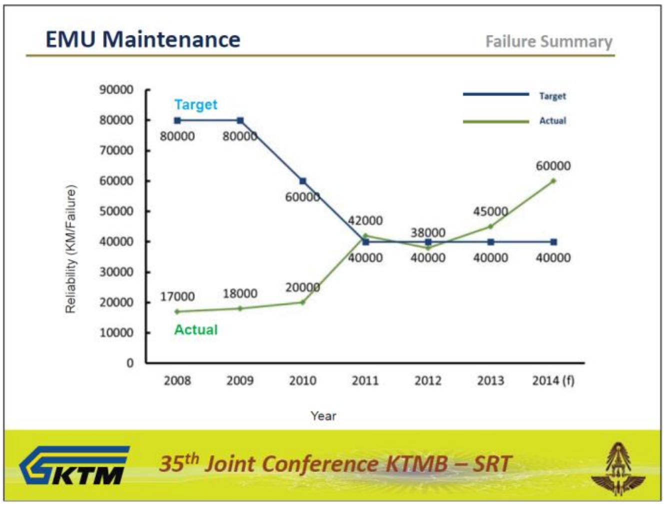

Fig. 2 KTMB's EMU reliability trend from year 2008 to 2014 (Jumain, 2014).

2. Methodology

This study employed a qualitative research method to obtain data and information to fulfil all the research objectives. The methodology involved secondary data collection from scholarly resources and past studies regarding PdM implementation, as primary data is obtained through semi-structured interviews with technically experience participants involved directly with the ECRL Project.

The research process began with the problem identification of the conducted research, followed by a comprehensive study on past case studies involving PdM, as qualitative research were chosen as the main approach. Then, a set of semi-structured interview questions were designed and segregated into multiple segments on addressing each of the research objectives.

Pilot test were arranged to refine the reliability and validity of the designed questions with the assistance of relevant professionals. Consequently, interview sessions involving stakeholders and experts that possesses at least 8 years of experience within the railway infrastructure management and maintenance were organized on gaining their technical expertise and views regarding the organizational readiness and expected challenges if the project desires to move forward with PdM approach.

In-depth content analysis through coding of responses were then conducted thoroughly before results interpretation took place. A research flowchart was developed to visualize the systematic progression of the study, which outlined the steps taken starting from problem identification, research design, instrument design, pilot testing, data collection, content analysis and final interpretation. Key decision points, such as modifications on interview questions following the pilot test, were highlighted to ensure clarity and transparency (refer Figure 3).

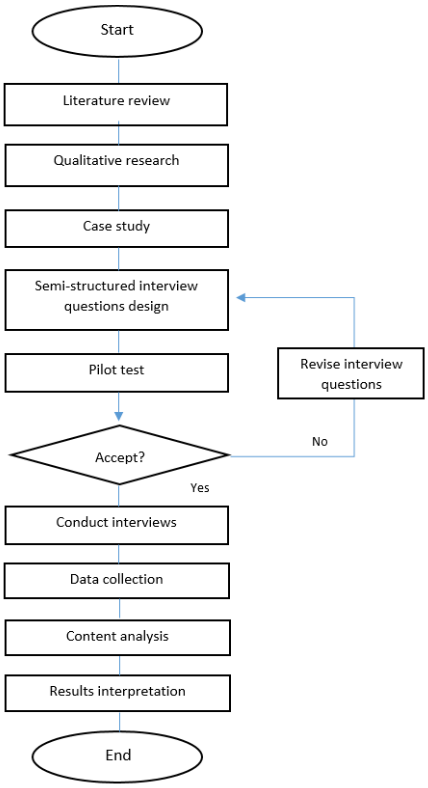

Fig. 3 Research flowchart

2.1 Qualitative Research

A qualitative research by utilizing past cast studies and semi-structured interview method has been considered for this research which revolve around narrative approach. Gathering invaluable input revolving around the ideas, perceptions and experiences from the related stakeholders that are involved directly to the ECRL project, in addition towards their decades of involvement within the development of the railway industry in Malaysia generally will be beneficial and helpful towards achieving each of the mentioned objective. To add, the strength of the qualitative research approach stems from its ability to analyse the opinions of both homogeneous and varied groups of people, thereby supporting communities in understanding the breadth of viewpoints within them. Responses gained from asking a group of people to specific questions and hypothetical situations will provide nuanced information which exceeds data obtained from surveys (Choy, 2014).

2.2 Semi-Structured Questions Design

The set of the interview questionnaires involves four different segments which is highlighted in Appendix A begins with the segment of collecting respondent background. Next, they are segregated into three different segments, with the aims to identify the factors towards the implementation of predictive maintenance within railway projects, to identify the barriers that constraint the adoption of predictive maintenance in managing railway infrastructure of the ECRL project and to determine ways to overcome the barriers that hinder the implementation of predictive maintenance within the infrastructure maintenance strategy of the ECRL project. By tailoring the interview questions within the scope of objectives thoroughly and accordingly, this approach contributed heavily on the detailed in-depth analysis of responses provided by each of the participant during the interviews.

2.3 Pilot Test

Pilot test provides visualization of certain problems that may occur during the main study, as well as to how data is collected and analysed (In, 2017). Therefore, a pilot test was carried out to assess the reliability of the interview questionnaire. The pilot test plays a crucial role in evaluating the effectiveness of the interview questionnaire, utilizing a multi-stage approach to ensure its refinement and clarification before being utilized for interviews. The main idea is to evaluate the effectiveness of the questionnaire by distributing it to participants which possessed technical comprehension and knowledge capacity of the scope of study, to collect their insightful feedback. Hence, careful analysis of the detailed feedback from an academician and four engineers gathered in Table 1 contributes to slight adjustments and refinements that were considered thoroughly for questions design improvement.

Table 1: Pilot Test's Feedback and Actions

Position	Feedback	Action to consider
Academician from Higher Institution	• Suggest a modification to the original sentence • Adjustment on wording • Highlights a concern regarding the vagueness in some questions, seeking further clarification on the specific.	• Improvise sentence structure. • Further clarify the question.
Senior Engineer	• Suggest a modification on the original sentence.	• Improvise sentence structure.
Engineer	• Suggest a modification on the original sentence.	• Improvise sentence structure.
Engineer	• Suggest a modification on the original sentence.	• Improvise sentence structure.
Engineer	• Unclear about the specific intention of the question and suggest modification on wording.	• Improvise sentence structure.

2.4 Data Collection

Secondary data were collectively gathered from journals, online articles and academic databases such as Google Scholar, ScienceDirect, ResearchGate and other relevant platforms. This process was designed to provide better clarity on the research topic. It comprised of topics such as maintenance strategy, existing strategies in PdM, benefits of utilising PdM and challenges in adapting to PdM. Primary data were obtained through semi-structured interview sessions with several key participants that are directly involved with the ongoing construction of ECRL Project. It includes key individuals within the System Division of MRLSB such as senior project engineers, project manager and senior project managers. It focused on capturing participants' perceptions, understanding and acknowledgement towards the possibility of adopting PdM as part of the infrastructure maintenance strategy of the ECRL Project operation phase.

2.5 Content Analysis

This research utilized a structural content analysis approach through a refined and structural coding process. Each coded response were structurally based on the existing themes from past studies or recurring themes emerged within the discussion. Then, the frequency of the codes appearing within each segment of discussion are highlighted in a statistical manner on aligning the basis of engineering technology application, despite the majority of the data obtained involves in-depth analysis from a qualitative approach. Then, data triangulation process involving each participant ensures the validity and consistency of data categorisation based on the outlined codes for each response.

3. Results and Discussion

This section presents the findings of the study through the conducted semi-structured interview sessions and discusses their implications, structured to cover both the results and their interpretation.

3.1 Respondent's Background

Table 2 provides a concise overview of the professionals involved within the ECRL Project, that have been interviewed in the various semi-structured interview sessions, each of whom brings a broad of expertise in managing the railway infrastructure and project, which too involve sustaining and maintaining the railway assets and operation. The table provides key details such as their positions, their respective companies, their roles in the current project and the total number of years they have been involved in the railway industry.

Table 2 Respondent's background

Participant	Position	Company	Roles in the project	Years of Experience in managing railway infrastructure & project
P1	Senior Engineer	MRLSB	Senior Rolling Stock Engineer	8 years
P2	Senior Engineer	MRLSB	Senior Maintenance Planning Engineer	17 years
P3	Project Manager	MRLSB	Head of Rolling Stock	15 years
P4	Senior Project Manager	MRLSB	Head of System Design	32 years
P5	Senior Project Manager	MRLSB	Head of System Construction	30 years

3.2 Factors influencing the implementation of predictive maintenance in railway

This segment represents the investigation of the factors that contributes towards the implementation of predictive maintenance (PdM) in railway industry, with the focus on gaining insights on experts' understanding on infrastructure maintenance strategy based on PdM, understanding the purpose of running PdM in their previous railway projects and examining the suitability of PdM based on the aspects of the ECRL Infrastructure.

3.2.1 Understanding on infrastructure maintenance strategy based on PdM

Table 3 represents the experts' understanding on infrastructure maintenance strategy based on implementing PdM, encompassing interview session conducted with each participant referred to as P1, P2, P3, P4 and P5. In overall, these perspectives reflect both the operational and technological rationale for adopting PdM, suggesting broad stakeholder recognition of its potential to modernize railway maintenance strategies. Operationally, PdM is valued for its ability to reduce downtime, extend asset lifespan, and align maintenance with long-term cost efficiency. Technologically, PdM is emphasized by its strength in strength in utilizing real-time data and trend analysis to assess actual asset conditions, marking a strategic shift from reactive or scheduled approaches. Together, these perspectives highlight PdM as a performance-enhancing and innovation-driven model for modern railway infrastructure management.

Table 3 Understanding on infrastructure maintenance strategy based on PdM

Participant	Understanding on infrastructure maintenance strategy based on PdM	Supporting quote
P1	Predictive maintenance involves proactively addressing potential issues in trains before failures occur, rather than waiting for breakdowns to happen.	*"For me, predictive maintenance is about not waiting for the trains to break down before we fix them."*
P2	Predictive maintenance represents a more intelligent and efficient approach to managing long-term asset performance, which goes further reactive repairs by enabling strategic maintenance planning.	"*I see it as a smarter, more efficient way to manage long-term asset performance. Not necessarily about fixing things, instead it is about planning better and optimize assets' lifespan"*
P3	Predictive maintenance utilises data from real-time equipment readings, trend analysis, and predictive modelling which inform maintenance decisions. Rather than relying on fixed schedules, actions are taken based on data-driven insights, resulting in a more precise and efficient approach.	*"The shifting from reactive or scheduled maintenance to a more strategic approach where we align maintenance with actual asset condition. It's all about using real-time readings from equipment, which guides maintenance decisions" P3 and P5*
P4	Predictive maintenance is about aligning maintenance strategies with long-term cost efficiency through the proper approach and optimized maintenance activities.	*"It is like having a digital eye on everything. It tells us what is wearing out or acting up before we even get there. Could really help cut down on cost & emergency work."*
P5	Predictive maintenance represents a transition from reactive or scheduled-based maintenance to a more strategic approach that aligns maintenance activities with the actual condition of assets and infrastructures.	*"The shifting from reactive or scheduled maintenance to a more strategic approach where we align maintenance with actual asset condition. It's all about using real-time readings from equipment, which guides maintenance decisions" P3 and P5*

3.2.2 Purpose of running PdM in railway projects

Figure 4 illustrates the distribution of codes derived from semi-structured interviews, capturing the perceived purposes of implementing PdM in railway projects from the perspective of each respondent. The frequency of each code indicates how commonly it was mentioned by participants (n = 5), serving as a proxy for consensus on strategic priorities in PdM adoption. The most prominent code, 'Cost Efficiency', was cited by all five participants. This reflects a shared understanding that PdM optimizes maintenance expenditure by enabling condition-based interventions, thereby minimizing unnecessary maintenance activities. To add, cost efficiency is strongly tied to proper allocation of resource, time and inventory management. "Reduced Unexpected Downtime" was mentioned twice (P1 & P4), reinforcing the operational value of PdM in improving service reliability and asset availability.

The second most frequently mentioned code, 'Manpower Optimization', appeared in three interviews (P2, P4, P5). From a technical standpoint, this highlights PdM's capability of PdM technology to address the need of maintenance accordingly and timely. This enables better workforce deployment strategy based on real-time asset health. Less frequently cited but still relevant, "Improved Safety" (P1) and "Introduction to Data Driven Concept" (P3) each appeared once. While these themes were not as prominent, they reflect a larger trend in engineering maintenance culture away from reactive techniques and toward predictive, analytics-based strategies that improve both technical integrity and long-term sustainability. Overall, the variety of data based on identified coding categories indicates the relevancy of PdM approach within the maintenance practices that exists within the modern day of railway industry.

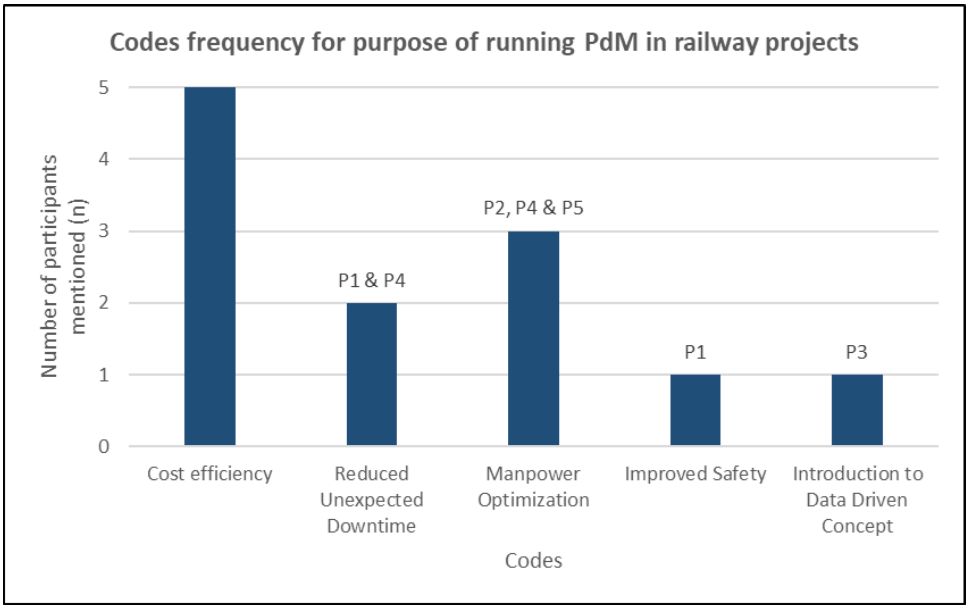

Fig. 4 Codes frequency for suitability of PdM based on the aspects of ECRL infrastructures

3.2.3 Suitability of PdM based on aspects of ECRL infrastructures

Figure 5 illustrates the distribution of codes obtained from semi-structured interviews providing the perceptions on suitability of PdM based on the aspects of ECRL infrastructures from the perspective of each respondent. The frequency of each code indicates how commonly it was mentioned by participants (n = 5), serving as a proxy for consensus on strategic priorities in PdM adoption. 'Optimization of CMMS' were mentioned by two participants (P1 & P4), reflecting the capability of optimizing Computerised Maintenance Management Systems (CMMS) through the integration with PdM's technology on enhancing asset management system. In addition, 'Real-Time Monitoring Capability' were addressed four times (P1, P3, P4 & P5) comprehensively. These responses implies the strong capability of PdM technology on providing real-time update on critical assets' lifespan. The early indication helps on assisting maintenance personnel for early intervention before breakdown occurs.

Meanwhile, 'Track Infrastructure Criticality' were mentioned twice (P3 & P5) emphasizing its importance towards ensuring the sustainability of operation. From their perspective, this implies the capability and suitability of PdM adoption on maintaining the most critical asset, at a time where it is considered as the most valuable infrastructure as the railway operation operates on a single-track line. Code 'Assets Quantity & Usage Intensity' has emerged within the discussion with three participants (P1, P2 & P5), suggesting the capability of PdM approach on improving the management of the sheer number of assets and its frequency of usage in the long run. Less frequently, code 'Remote-Monitoring Compatibility' has been mentioned by one participant (P2). addressing its capability on monitoring capability in hardly accessible areas without proper access road. Overall, the emergence of the existing and new codes from past studies and this section's discussion respectively, have further emphasized the suitability and critical aspects of ECRL infrastructures that drives the adoption of PdM approach into its maintenance practices into the project operation phase.

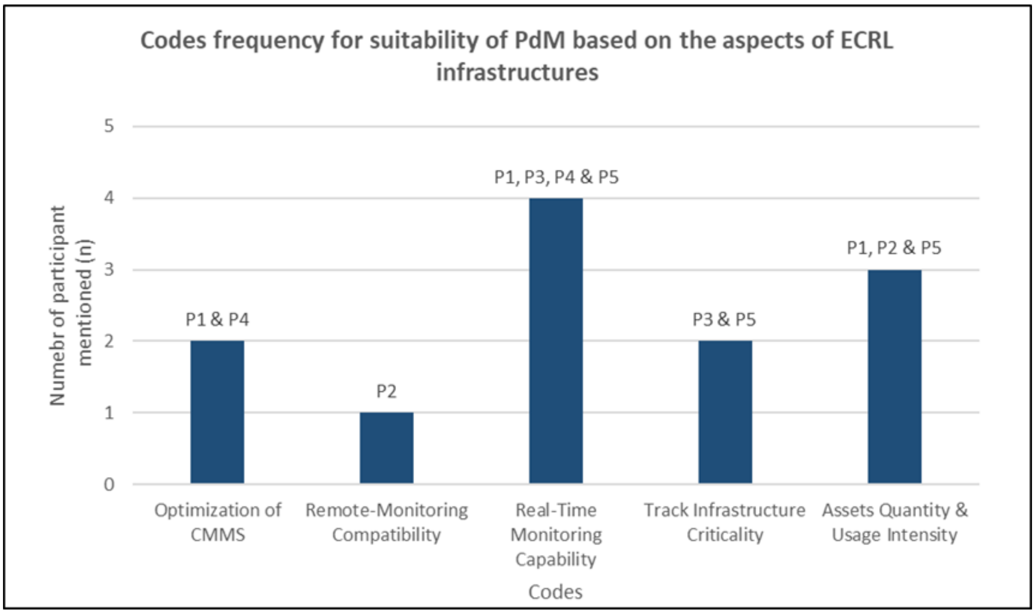

Fig 5 Codes frequency for suitability of PdM based on the aspects of ECRL infrastructures

3.3 Barriers constraining the adoption of PdM in managing railway infrastructures

This segment represents the investigation of the barriers that constraints the adoption of predictive maintenance in the railway industry based on the experience of the involved participants. Besides, it also addresses the challenges, risks, and constraints that may hinder the adoption of predictive maintenance in the ECRL project.

3.3.1 Main barriers in transitioning from traditional maintenance to PdM in railway projects

Figure 6 highlights the distribution of codes acquired from the interviews discussion regarding the barriers in transitioning from traditional maintenance to PdM in railway projects based on each participant experience. The frequency of each code indicates how commonly it was mentioned by participants (n = 5), serving as a proxy for consensus on existing barriers within the transition. The most prominent code, 'High Initial Investment & Implementation Cost', was mentioned by all five participants. This reflects a collective understanding regarding the high implementation cost required for PdM technology together with its systems, software and staff trainings for its adoption. Two participants (P3 & P5) cited code 'Limitation on Data Quality & Availability', indicating the importance of storing relevant and appropriate data for assets performance assessment by PdM. Code 'Skills Gap' has been mentioned by three participants (P1, P2 & P3), advocating the criticality of proper competency and comprehensive training requirements on managing assets through PdM technology.

In addition, three participants (P2, P4 & P5) have addressed the code 'Management and Cultural Resistance' within the discussion. It provides the indication on the lack of acceptance and willingness of members of organisation on shifting towards a more robust but complicated approach within their existing maintenance approach. Code 'Unclear Planning & Policy' too has emerged within the discussion of two participants (P1 & P3). Participants emphasized the lack of establishing clear and well-written policy on improving the existing maintenance practices as part of the main barriers on driving PdM adoption within railway projects. In overall, this section have identified the main barriers in transitioning from traditional maintenance into PdM in railway projects. The emergence of multiple of similar codes within the discussion involving all participants proved the need of acknowledging these barriers crucially on driving PdM adoption into railway projects.

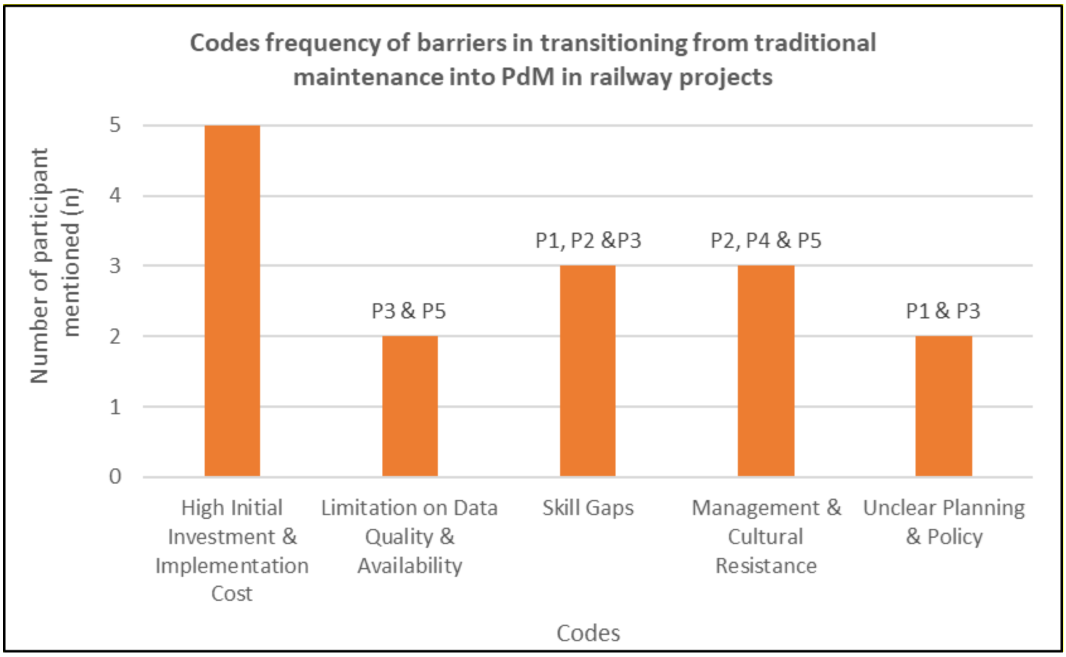

Fig. 6 Codes frequency of barriers in transitioning from traditional maintenance into PdM in railway projects

3.3.2 Barriers that are hindering the adoption of PdM in the ECRL Project

Figure 7 illustrates the distribution of codes obtained from semi-structured interviews providing the barriers that are hindering the adoption of PdM in the ECRL Project ECRL from the perspective of each respondent. The frequency of each code indicates how commonly it was mentioned by participants (n = 5), serving as a proxy for consensus on barriers that hindering PdM adoption into the project. The most prominent code emerged as 'Technical & Skill Gaps' were heavily mentioned by four participants (P1, P2, P3 & P4). It implies the lack of exposure and experience working within the technical workflow and standards of the Chinese railway industry as the biggest barrier within the project. Three participants (P1, P3 & P5) cited code 'Organizational Readiness Varies', indicating that driving PdM adoption as the least priority within the organisation, resulting to lack of coordination for its adoption plan in the future. Code 'Lack of Perception on PdM Benefits' were developed within the discussion with two participants (P3 & P4]. This addresses their concern regarding PdM's capability less recognition and awareness among the organisation members.

Then, two participants (P4 & P5) addressed the code 'Multinational Coordination Challenge' within the challenges, that implies the criticality of involvement of two international entities in the presence of MRLSB and CCCC, on achieving mutual budget and technical cooperation on driving PdM adoption into the project. Less frequently, code 'Low familiarity with Data Management' emerged based on the response of one participant (P3). This indicates the hurdles on driving PdM approach without establishing workers with the basic of data literacy from data collection and real-time data interpretation from the technology itself. In overall, this section highlights multiple codes that have emerged within the discussion. The emergence of different pattern of code

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frequency implies the variety of barriers that exists within the project from the perspective of each participant that is directly involved to the project.

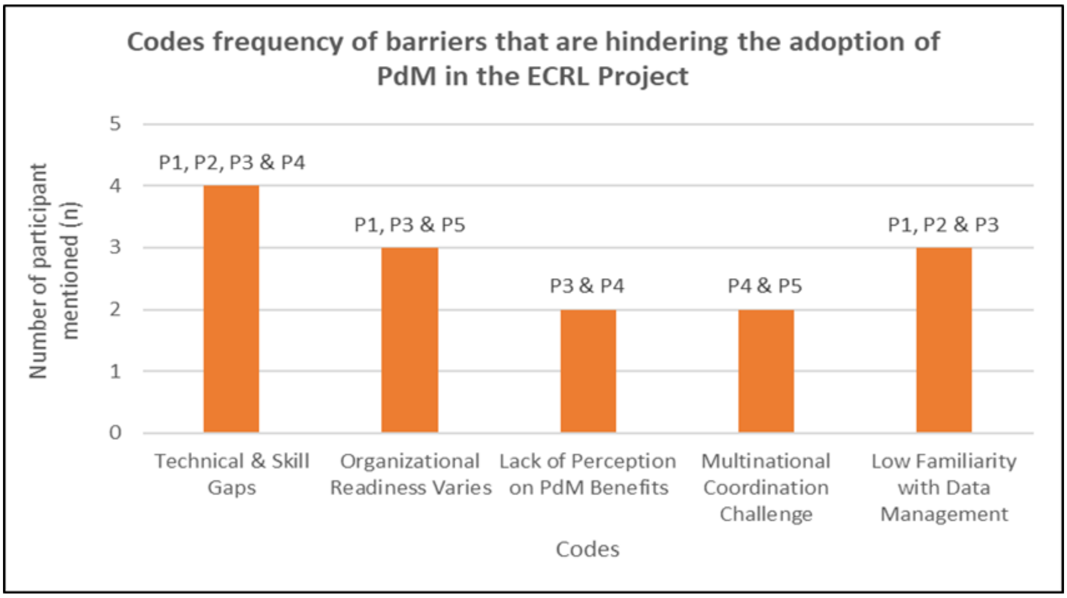

Fig. 7 Codes frequency of barriers that are hindering the adoption of PdM in the ECRL Project

3.4 Ways to overcome the barriers that constraint PdM implementation within ECRL Project's infrastructure maintenance strategy

This segment represents the investigation on the ways to overcome the barriers that constraint the adoption of PdM within the infrastructure maintenance strategy based on the observation and experience of involved participants. It addresses the preparation measures that drives the workforce in driving the adoption of PdM and suggest on the ways leadership support could be strengthen to drive the adoption of PdM in the ECRL project.

3.4.1 Suggestion on preparation measures to be taken within the workforce in driving the adoption of PdM

Figure 8 highlights the distribution of codes obtained from semi-structured interviews encompassing the suggestion on preparation measures within the workforce in driving the adoption of PdM into the ECRL Project based on the perspective of each respondent. The frequency of each code indicates how commonly it was mentioned by participants (n = 5), serving as a proxy for consensus on preparation measures to be considered for PdM adoption into the project. Unsurprisingly, code 'Investment in Training and Competency' have merged within the discussion will all participants comprehensively. This reflects the seriousness on directing capital investment towards reliable and capable technology of PdM through its standardized systems, equipment and training on improving the maintenance approaches in long term. Three participants (P1, P2 & P3) hinted code 'Establishing Data Handling & Management Workflow' concisely, implying the importance of constructing a structural framework on data management.

Notably, one participant (P3) have cited code 'Encouraging Bottom-Up Feedback' within the suggestions. This advocates the need of bridging the gap between leaders and ground level workers by having the proper platform on gaining the insightful information and perception towards ongoing practices. Two participants (P4 & P5) have mentioned code 'Empowering Technology Transfer', suggesting the further utilisation of the existing technology transfer platform between both MRLSB and CCCC enhances the possibility of adopting PdM approach strategically. In addition, code 'Education and Awareness' have been cited by two participants (P2 & P5). This indicates the importance of establishing a proper education framework within targeted working groups on ensuring the awareness and continuous improvement of maintenance practices especially involving PdM approach. In summary, this section summarizes the emergence of multiple codes within the discussion of preparation measures for workforce in driving the adoption of PdM strategically. It comprises the perspective of financial, policies and structural frameworks, which are critical on developing the solution for this matter.

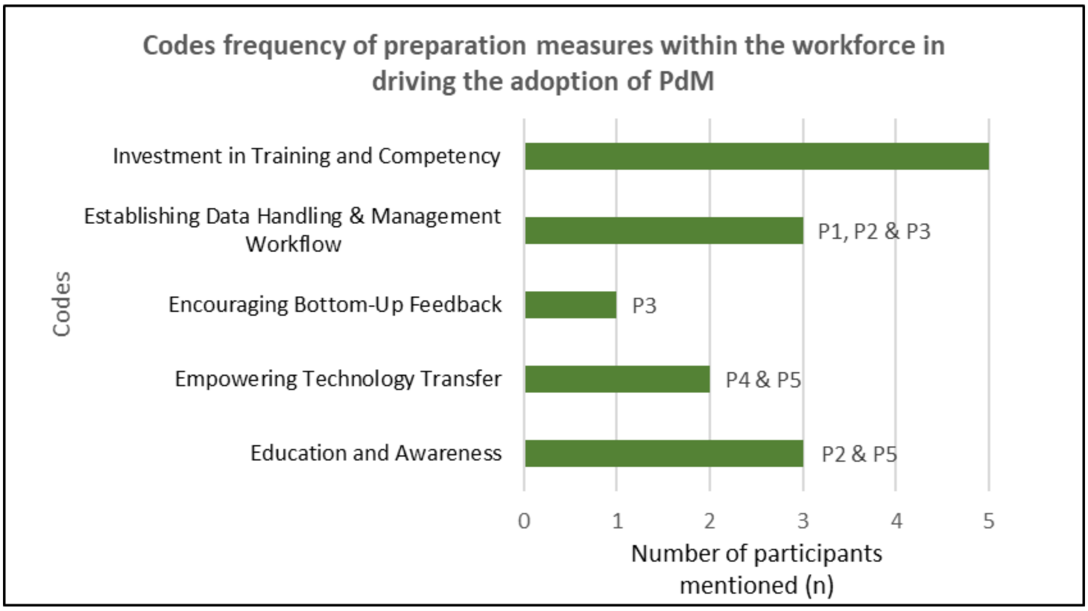

Fig. 8 Codes frequency of preparation measures within the workforce in driving the adoption of PdM

3.4.2 Suggestion on strengthening top leadership support towards the adoption of the PdM in the ECRL Project

Figure 9 illustrates the distribution of codes obtained from semi-structured interviews emphasizing the suggestion on strengthening top leadership support towards the adoption of PdM into the ECRL Project from the perspective of each participant. The frequency of each code indicates how commonly it was mentioned by participants (n = 5), serving as a proxy for consensus on suggestions on strengthening top leadership support for PdM adoption into the project. All participants have collectively agreed on code 'Investment and Resource Commitment' as core on strengthening leadership support. This reflects the criticality of proper long-term investment and allocation of budget for PdM adoption on paving continuous improvement that comprises standardized training, technology selection and equipment upgrades strategically. Three participants (P1, P2 & P3) mentioned code 'Establishing Strategic PdM Policy' within their suggestions, which implies the importance of aligning the purposes, scopes and direction of PdM implementation through a standardized policy framework.

Notably, three participants (P3, P4 & P5) have emphasized code 'Feedback & Sharing Platform' as a way of strengthening leadership support towards PdM adoption. This indicates the crucial role of a designated platform that enables proper feedback and information to channel through from ground level workers towards their top leadership systematically. It contributes significantly towards continuous improvement at all stages of implementation. Two participants (P1 & P3) hinted code 'Government Collaboration and Support' concisely, implying the importance of fostering strategic relationship and partnership with relevant authorities such Ministry of Science. Technology and Innovation (MOSTI), that ensures continuous establishment of upskilling programs and incentive supports on boosting PdM technology adoption. Comprehensively, two participants (P2 & P4) cited code 'Change Management' on boosting the leadership support. This emphasizes the need of strategic approach within leadership engagement to drive continuous participation and acceptance from organisation members at all levels towards a change of scalability of PdM. In overall, this section provides clarity towards the ways of strengthening leadership support towards PdM adoption from the emergence of multiple codes throughout the interview discussions.

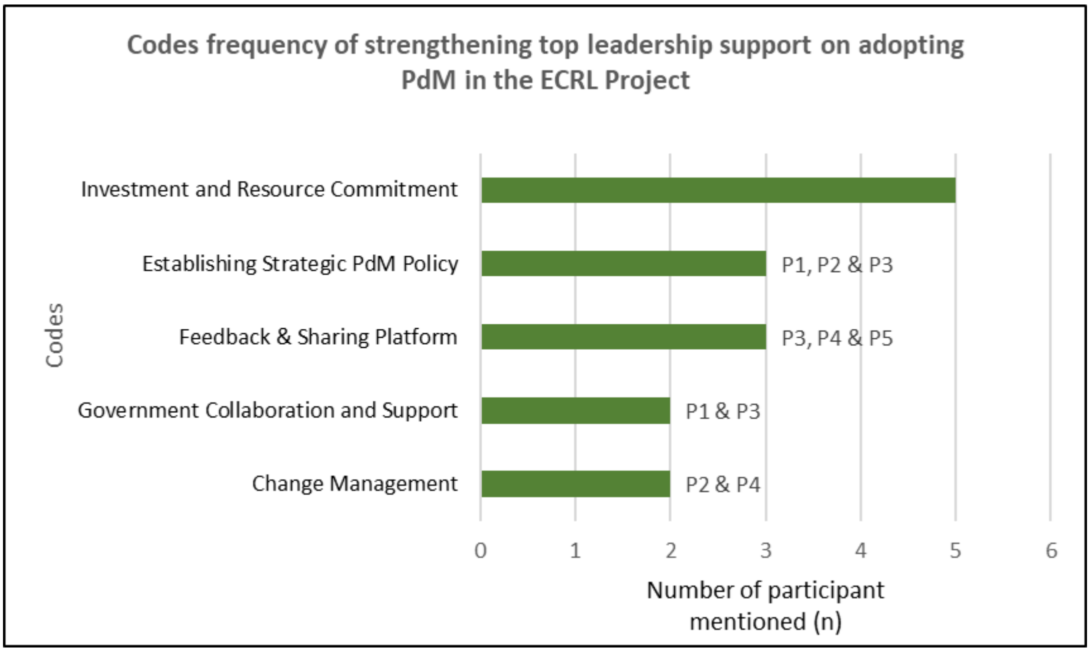

Fig. 9 Codes frequency of strengthening top leadership support on adopting PdM in the ECRL Project

4. Conclusion

This research provides an investigation on infrastructure maintenance strategy of the ECRL Project operation phase based on implementing predictive maintenance (PdM). By thorough analysis of literature and in-depth interviews conducted for data collection, the study achieves its research objectives through valuable views and insights gathered into the factors that influence the adoption of PdM in railway industry, the barriers that constraint PdM adoption in managing railway infrastructure of the ECRL Project and suggested ways on overcoming the barriers that hinder the adoption of PdM into the project. While the foundation of this research is qualitative, descriptive statistics were applied to analyze code frequency and participant consensus. This contributed in transforming insights into measurable outputs, ensuring alignment with engineering technology expectations and improving clarity for constructing decision-making frameworks. However, the research has its own limitations in which has been identified as limited time to find participant replacement, large volumes of narrative data for coding process and controlling the flow of interviews. To address these challenges, several recommendations are proposed for future research considerations; to include relevant data such as maintenance record and performance for when the ECRL operation has begun so that better understanding and analysis could be drawn on justifying the of PdM; to conduct initial briefing on methodology involved clearly to participant before starting the actual interview for better flow engagement; and to shift into structured interview questionnaires that utilises quantitative approach to reach better engagements of results from a large group of respondents. With refinement, this study yields valuable resources for researchers, industry practioners and decision-makers that seeks the potential of improving their maintenance practices by strategically adopting predictive maintenance (PdM) especially for ECRL Project in particular.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **Implementing Predictive Maintenance (PdM) Strategy for Infrastructure in the ECRL Project Operation Phase**: Mohamad Safwan Na'im Ridzuan, Corresponding Author: Prof. Madya. Ts. Dr. Joewono Prasetijo and Firdaus Abd Rahman. All authors reviewed the results and approved the final version of the manuscript.

Appendix A: Interview Questions

Segment A: Respondent's background

This segment clarifies the information regarding respondent's background

1. Full name
2. Position
3. Company
4. Roles
5. Years of experience in managing railway infrastructure and project

Segment B: Factors Influencing the Implementation of Predictive Maintenance

This segment explores the driving factors, motivations, and enablers for adopting predictive maintenance in railway projects.

1. What do you understand on infrastructure maintenance strategy by implementing predictive maintenance?
2. What was the purpose of running Predictive Maintenance in any of the railway projects you have been part of before?
3. Based on your judgement, which specific aspects of the ECRL infrastructure make it suitable for predictive maintenance?

Segment C: Barriers Constraining the Adoption of Predictive Maintenance

This segment identifies challenges, risks, and constraints that may hinder the adoption of predictive maintenance in the ECRL project.

1. What do you consider to be the main barriers in transitioning from traditional maintenance to PdM in railway projects?
2. Based on your observation, what are the barriers that are currently hindering the adoption of PdM in the ECRL Project?

Segment D: Overcoming Barriers to Predictive Maintenance Implementation

This segment explores strategies, resources, and actions needed from both workforces and top leadership to overcome the barriers identified in the previous segment.

1. Based on your experience, what kind of preparation measures within the workforce could be taken for implementing predictive maintenance?
2. In your opinion, how can top leadership support be strengthened to drive the adoption of predictive maintenance in the ECRL project in the future?

Appendix B: Interview questions

Prepared by	Verified by	Verified by
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References

Alaswad, S., & Xiang, Y. (2016). *A review on condition-based maintenance optimization models for stochastically deteriorating system*. Reliability Engineering & System Safety, 157, 54–63. https://doi.org/10.1016/j.ress.2016.08.009

Bernama. (2024, December 7). *MRL confirms ECRL partnership plans with CCCC remain unchanged*. BERNAMA. https://bernama.com/en/news.php?id=2317022

China Construction Communication Company. (2022). *ECRL Project Infrastructure Maintenance Strategy and Management Report*. Unpublished manuscript

Choy, L. T. (2014). *The Strengths and Weaknesses of Research Methodology: Comparison and Complimentary between Qualitative and Quantitative Approaches*. IOSR Journal of Humanities and Social Science, 19(4), 99–104. https://doi.org/10.9790/0837-194399104

De Bruin, T., Verbert, K., & Babuska, R. (2017). *Railway Track Circuit Fault Diagnosis Using Recurrent Neural Networks*. IEEE Transactions on Neural Networks and Learning Systems, 28(3), 523–533. https://doi.org/10.1109/tnnls.2016.2551940

Griffiths, B. (2022). *Predictive Maintenance for The Railway: Benefits & Risks*. Littlefish. https://www.littlefish.co.uk/insights/predictive-maintenance-for-the-railway/

In, J. (2017). *Introduction of a pilot study.* Korean Journal of Anesthesiology 2017; 70(6): pp601-605

Jumain, I. (2014). (Ed.). *Maintenance Enhancement of Electrical Multiple Unit (EMU) by KTMB*. Unpublished manuscript.

Keizer, M. C. O., Flapper, S. D. P., & Teunter, R. H. (2017). *Condition-based maintenance policies for systems with multiple dependent components: A review*. European Journal of Operational Research, 261(2), 405–420. https://doi.org/10.1016/j.ejor.2017.02.044

Lidén, T. (2015). *Railway Infrastructure Maintenance - A Survey of Planning Problems and Conducted Research*. Transportation Research Procedia, 10, 574–583. https://doi.org/10.1016/j.trpro.2015.09.011

Smith, P. R. (2018). *Collecting sufficient evidence when conducting a case study*. The Qualitative Report, 23(5), 1043-1048. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=collecting+sufficient+evidence+when+conducting&btnG=

Vatn, J., & Aven, T. (2019). *An approach to maintenance optimization where safety issues are important.* Reliability Engineering & System Safety, 95(1), 58–63. https://doi.org/10.1016/j.ress.2009.06.002

Yan, J., Meng, Y., Lu, L., & Li, L. (2017). *Industrial Big Data in an Industry 4.0 Environment: Challenges, Schemes, and Applications for Predictive Maintenance*. IEEE Access, 5, 23484–23491. https://doi.org/10.1109/access.2017.2765544