UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
ESCOLA DE ENGENHARIA
PROGRAMA DE PÓS-GRADUAÇÃO MESTRADO PROFISSIONAL EM ENGENHARIA DE PRODUÇÃO

Michael Luciano Chaves Franz

INDUSTRY 4.0 IN THE CONTEXT OF PASSENGER RAILWAY COMPANIES

Porto Alegre
2023

Michael Luciano Chaves Franz

INDUSTRY 4.0 IN THE CONTEXT OF PASSENGER RAILWAY COMPANIES

Dissertação submetida ao Programa de Pós-Graduação Mestrado Profissional em Engenharia de Produção da Universidade Federal do Rio Grande do Sul como requisito parcial à obtenção do título de Mestre em Engenharia de Produção, modalidade Profissional, na área de concentração em Sistemas de Produção.

Orientador: Professor Néstor Fabián Ayala, Dr.

Porto Alegre

2023

Michael Luciano Chaves Franz

INDUSTRY 4.0 IN THE CONTEXT OF PASSENGER RAILWAY COMPANIES

Esta dissertação foi julgada adequada para a obtenção do título de Mestre em Engenharia de Produção na modalidade Profissional e aprovada em sua forma final pelo Orientador e pela Banca Examinadora designada pelo Programa de Pós-Graduação Mestrado Profissional em Engenharia de Produção da Universidade Federal do Rio Grande do Sul.

_____

Prof. Néstor Fabián Ayala, Dr.
Orientador PMPEP / UFRGS

_____

Prof. Ricardo Augusto Cassel, Ph.D.
Coordenador PMPEP / UFRGS

Banca Examinadora:

Professor Diego de Castro Fettermann, Dr. (UFSC)

Professor Dusan Schreiber, Dr. (FEEVALE)

Professor Jonatas Ost Scherer, Dr. (UFRGS)

Dedicatória

Aos meus filhos, Filipe e Elisa, a minha esposa,

Camila, e aos meus pais, Vilmar e Ana

AGRADECIMENTOS

Agradeço primeiramente a Deus pelo dom da vida, e por se fazer presente em todos os momentos de forma clara e próxima.

Agradeço a minha querida esposa, Camila Scotta Franz, por estar sempre ao meu lado, apoiando nos projetos que a vida nos oferece, como a realização desta dissertação. Meus filhos, Filipe Scotta Franz (11 anos) e Elisa Scotta Franz (4 anos), agradeço a alegria e realização que são em minha vida. Deixo aqui registrado que por muitos momentos senti deixar vocês para realizar este mestrado. Uma de minhas maiores motivações era instigar o valor do trabalho e do esforço em vocês, e acredito que um dia entenderão plenamente.

Agradeço a meus pais, Vilmar Franz e Ana Maria de Freitas Chaves Franz, que se sacrificaram pela minha formação humana e profissional. Em especial, agradeço a minha mãe que apoiou muito na realização deste curso que se encerra na conclusão deste trabalho.

Agradeço ao meu professor e orientador, Néstor Fabián Ayala, sempre presente e amigável, que me ensinou magistralmente os fundamentos da Quarta Revolução Industrial e soube conduzir os detalhes que deram forma ao trabalho.

Agradeço aos professores que compuseram a banca examinadora, pelo tempo dedicado para leitura e observações realizadas que contribuíram para aperfeiçoamento deste trabalho.

Agradeço aos professores da pós-graduação em engenharia de produção da UFRGS, aprendemos muito com vocês. E agradeço aos colegas que conhecemos durante o curso, companheiros de muitas horas dedicadas na realização deste sonho. Alguns já podemos chamar de amigos.

Agradeço aos colegas da ferrovia de passageiros no Brasil pelos conhecimentos compartilhados, pelas horas dedicadas, e pelas oportunidades oferecidas.

A todos que de forma direta ou indireta contribuíram para a realização deste trabalho, meu muito obrigado.

RESUMO

A Indústria 4.0 tem sido um tema de pesquisa crescente e tem chamado a atenção de países desenvolvidos e emergentes que buscam uma posição de destaque neste novo cenário industrial. O setor ferroviário é um segmento relevante para o transporte de pessoas e mercadorias. No entanto, a literatura que une o tema Indústria 4.0 e ferrovias ainda precisa ser explorada. Na prática, há mais estudos partindo de uma determinada tecnologia em evidência. Assim, este trabalho levanta uma questão importante: como os conceitos da Indústria 4.0 podem ser aplicados às empresas ferroviárias de passageiros holisticamente? Utilizamos uma abordagem exploratória e qualitativa para analisar este importante setor, considerando a escassez de estudos com a visão abrangente pretendida. Entrevistamos especialistas de oito operadoras de transporte e de quatro fornecedores de tecnologia do segmento ferroviário brasileiro. Os resultados foram agrupados em um modelo de oportunidades e indicam que as empresas estão se movendo em direção a um centro de inteligência operacional para implementar oferta de trens robusta e eficiente, manutenção prescritiva, gerenciamento robusto da cadeia de suprimentos, melhor experiência dos passageiros e desempenho dos trabalhadores. Desenvolvemos e testamos um modelo de maturidade da Indústria 4.0 para operadoras ferroviárias de passageiros com base em nossas descobertas empíricas e nos principais indicadores de desempenho das empresas brasileiras. Recebemos retorno positivo de que o modelo retrata as preocupações diárias dos profissionais que trabalham para rodar o negócio e que os estágios de maturidade propostos representam um caminho para alavancar as métricas associadas aos objetivos produtivos definidos com ajuda dos indicadores de desempenho do setor. A contribuição prática da pesquisa é auxiliar as empresas ferroviárias de passageiros a planejar a jornada da Indústria 4.0 em seu segmento, tanto na concepção de novas linhas de trens quanto na busca por sistemas em operação mais sustentáveis. O estudo traz uma contribuição acadêmica significativa, pois os modelos com essa visão holística da Quarta Revolução Industrial no transporte ferroviário de passageiros são inéditos.

Palavras-chave: Indústria 4.0, empresas ferroviárias de passageiros, transporte ferroviário, transformação digital.

ABSTRACT

Industry 4.0 has been a growing research topic and has drawn the attention of developed and emerging countries that seek a prominent position in this new industrial scenario. The railway sector is a relevant segment for transporting people and goods. However, the literature joining the theme of Industry 4.0 and railways still needs to be explored. In practice, there are more studies from a determined technology in evidence. Thus, this dissertation raises an important question: How can the Industry 4.0 concepts be applied to passenger railway companies holistically? We used an exploratory and qualitative approach to analyze this important sector, considering the scarcity of studies with the intended embracing vision. We interviewed experts from eight transport operators and four technology providers in the Brazilian railway segment. The results were grouped into an opportunities model, indicating that companies are moving towards an operational intelligence center to implement robust and efficient train offers, prescriptive maintenance, strong supply chain management, and improved passenger experience and worker performance. We developed and tested an Industry 4.0 maturity model for passenger railway companies based on our empirical findings and the Brazilian companies' main Key Performance Indicators (KPIs). We received positive feedback that the model portrays the daily concerns of professionals who work to run the business and that the proposed maturity stages represent a way to leverage the metrics associated with the productive objectives defined with the help of the sector's KPIs. The practical contribution of the research is to help passenger railway companies plan the Industry 4.0 journey in their segment, both in designing new train lines and looking for more sustainable systems in operation. The study delivers a significant academic contribution as the frameworks with this holistic view of the Fourth Industrial Revolution in the passenger railway are unprecedented.

Keywords: Industry 4.0, passenger railway companies, rail transport, digital transformation.

LISTA DE FIGURAS

LISTA DE TABELAS

SUMÁRIO

1 INTRODUCTION

1.1 Initial commentaries and dissertation theme

Industry 4.0 has been a growing research topic since this concept coining (Meindl et al., 2021), following a global trend of developed economies and emerging countries, each with its public policies seeking a prominent position in this new industrial scenario (Liao et al., 2017). Several rising technologies are combined to provide digital solutions, allowing for connected and smart enterprise activities, leveraging new ways of handling data and new business strategies (Frank, Dalenogare, & Ayala, 2019).

As Germany has one of the most competitive manufacturing industries globally, the concept of Industry 4.0 emerged in 2011 through a German initiative of the federal government, academy, and private companies to keep it at the technological forefront of equipment manufacturing and complex industrial processes management (Kagermann, Wahslter, & Helbing, 2013). Industry 4.0 is the Fourth Industrial Revolution, based on Cyber-Physical Systems, the convergence of physical and virtual worlds (Xu, Xu, & Li, 2018; Liao et al., 2017). This relation occurs because the first time was possible to network objects, people, resources, and information systems to create the Internet of Things and Services (Kagermann, Wahslter, & Helbing, 2013).

Industry 4.0 was born with manufacturing as a central element (Kagermann, Wahslter, & Helbing, 2013) that continues as the protagonist (Frank, Dalenogare, & Ayala, 2019). However, other aspects have become relevant over the years, such as the human role in working activities, supply chain communication and integration, and how products and services are offered (Meindl et al., 2021).

The model proposed by Frank, Dalenogare, and Ayala (2019) has stood out with its vision, the Four Smarts of Industry 4.0. It considers four smart dimensions as front-end technologies, each encompassing a specific subset of technologies concerned with an enterprise's operational (internal) and market (external dimensions) needs. Moreover, considers other base technologies that provide connectivity and

intelligence for front-end technologies, boosting the enterprises' digital transformation into the Fourth Industrial Revolution (Meindl et al., 2021). As shown in Figure 1, Smart Manufacturing is the central dimension of Industry 4.0, with the other front-end technologies joining it, supporting the enterprises' value chain in the internal and external business dimensions.

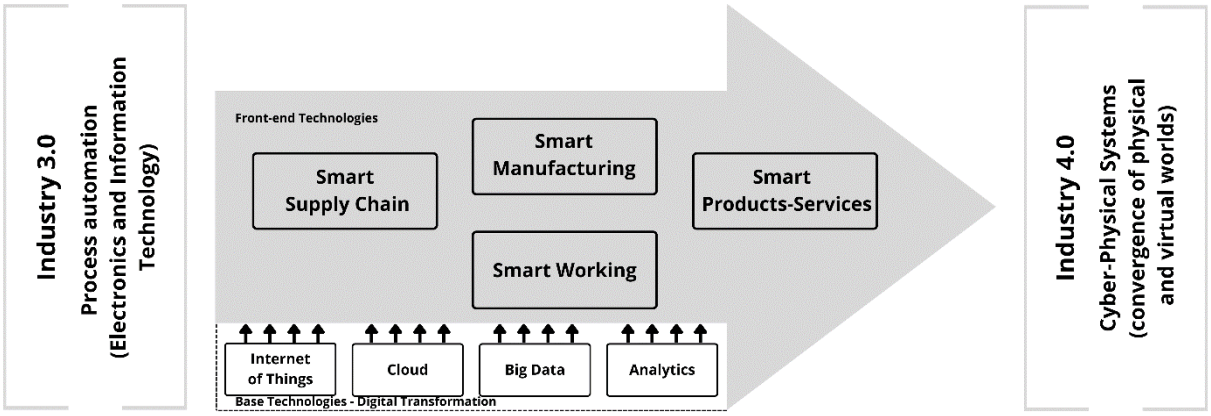

Figure 1 - The Four Smarts of Industry 4.0. Adapted from Frank, Dalenogare, and Ayala (2019)

Other areas beyond the manufacturing industry, such as healthcare systems (Tortorella et al., 2019), education (Hussin, 2018), and cities (Lom, Pribyl, & Svitek, 2016), have their Industry 4.0 concept and principles envisioning benefits. In the railway sector, a worldwide priority when thinking about smart, environmentally, and user-friendly mobility systems (Pieriegud, 2018), few papers explore the Industry 4.0 benefits, especially regarding demonstrating how to apply the concepts involved holistically.

Laiton-Bonadiez et al. (2022) systematically reviewed the recent literature to find out the main problems the academic community has studied to support the demands of the railway sector and which Industry 4.0 technologies have the potential to solve the issues faced. The paper results show three study domains: (i) monitoring, (ii) decision and planning techniques, and (iii) communication and security. Each, with its subdomains and associated technologies, often combined to generate the expected benefits. Finally, the authors listed nine Industry 4.0 technologies that provide solutions for the current demands of the railway: (i) Artificial Intelligence, (ii) Internet of Things (IoT), (iii) Modelling and Simulation, (iv) Smart Decision Support Systems, (v) Big Data, (vi) Computer Vision, (vii) Cybersecurity, (viii) Virtual Reality, and (ix) Cloud

Computing. The emphasis on selected articles is notably on Artificial Intelligence and the Internet of Things.

Gerhátová, Zitrický, and Klapita (2021), and Gerhátová, Zitrický, and Gašparik (2021) investigated opportunities to apply Industry 4.0 concepts in rail transport. They evaluated opportunities for digitalization and automation of wagon marking processes at some Slovakia dispatch stations and some activities (train arrival notification, shipping documents processing, transport and customs control on the train) at a station on the Slovak-Ukrainian border where customs office procedure significantly affects international goods transport time. According to the authors, IoT, Big Data, Smart Cameras and Sensors, Artificial Intelligence, Computer Vision, 3D Scanning, Mobile Devices, and Drones can contribute to the freight rail transport attractiveness in Europe.

Kans, Galar, and Thaduri (2016) described applications of Industry 4.0 technologies in rail transport assets maintenance. They discuss their positive effects on Swedish companies in the segment. Some expected benefits are an operational environment supported by Information and Communication Technologies (ICT), critical assets prognosis, real-time trains identification and location using RFID, and networking and knowledge-sharing tools between workers. Visual tools such as BI (Business Intelligence) would report asset health, spare parts arrival forecast, and technical inspection results, integrating operation and maintenance data for decision-making.

Bustos et al. (2021) addressed the technological updating of trains manufactured before Industry 4.0. The authors encourage enjoying the benefits of connectivity and monitoring rolling stock towards diagnosing incipient failures and improving maintenance planning and components design. The idea is to transform pre-Industry 4.0 trains into connected Rolling Stock (Cyber Physical System).

Some other papers discuss base Industry 4.0 technologies in railways from the perspective of technology in evidence, as in the following examples. Tang et al. (2022), Mulongo, Mnkandla, and Kanakana-Katumba (2021), and Besinovi et al. (2021) evaluated Artificial Intelligence as a key factor of competitiveness and raised existing and potential applications in the railway. Jo, Kim, and Kim (2018) and Li et al.

(2017) studied IoT to achieve a smart railway infrastructure and collect information over a wide operational area. Ghofrani et al. (2018) verified studies on Big Data Analytics in rail transport systems identifying three main areas: maintenance, operations, and safety.

Reviewing the recent literature, we have not found a study with a holistic view of Industry 4.0 in rail transport. Nor an Industry 4.0 implementation model in this sense. Therefore, the theme of this dissertation is the concept of Industry 4.0 in the context of the railway industry. This study evaluates how the technologies transforming the world economy's secondary sector can leverage the transport modal that has been important since its emergence in the first industrial revolution. Moreover, it is concerned to suggest a holistic Industry 4.0 implementation model for passenger railway companies in this segment, considering internal and external business dimensions, following the emerging literature.

1.2 Research justification

Since its beginning, the railway has played an important role in transporting goods and people being considered an important issue in the economic growth of nations (Laiton-Bonadiez et al., 2022; Gerhátová, Zitrický, & Klapita, 2021; Gerhátová, Zitrický, & Gašparik, 2021; Jo, Kim, & Kim, 2018; Pieriegud, 2018). Freight rail transport is a good option for moving large loads over long distances, generating economic and environmental benefits compared to other freight transport modes (Gerhátová, Zitrický, & Klapita, 2021; Gerhátová, Zitrický, & Gašparik, 2021). Passenger rail transport creates many benefits for major cities because of its punctuality, transportation capacity, and use of clean energy (Wang et al., 2018).

The railway is the central means for the massive displacement of the population within cities and between them in large metropolitan centers (Jo, Kim, & Kim, 2018). According to Brazil's national association of passenger rail transport (ANPTrilhos, 2017), only the railway effectively deals with peak passenger demand in large Brazilian cities while making travel less impactful on the environment than other transportation modes. Some benefits are regularity in services provision, time and cost

savings in urban displacements, fewer traffic accidents and congestion, air and public spaces quality, noise pollution reduction, and even zero pollutants emission in the case of electrified systems. Figure 2 reinforces this perception by comparing the number of passengers transported per hour/direction/traffic lane implemented (on the left) and the need for urban space to move the same mass of people (on the right) between the train, bus, and car transport modes.

Figure 2 - Comparison between train, bus, and car transport modes. Adapted from ANPTrilhos (2017)

Railway technology has followed the progress of industrial revolutions, from creating the steam locomotive in the 19th century, replacing animal traction, and consecrating the horsepower unit measurement, to the emergence of high-speed trains in the mid-20th century (Jo, Kim, & Kim, 2018). Although, the literature involving the theme of Industry 4.0 and railways still needs to be explored. In practice, there are more studies from a determined technology in evidence.

Given this, we raise an important question: How can the Industry 4.0 concepts be applied holistically to passenger railway companies? As far as we know, there is no integrated vision for systematically implementing Industry 4.0 in the railway considering all business dimensions. Furthermore, to study the opportunities in this important sector, we adopted the model suggested by Frank, Dalenogare, and Ayala (2019), which is already internationally accepted in the literature (Meindl et al., 2021). The model considers a broad vision of the Fourth Industrial Revolution, which can help us holistic explore potential technologies to elevate the railway into the new industrial age.

1.3 Objectives

This dissertation aims to verify how the concept of Industry 4.0 can be holistically applied in passenger rail transport and propose an implementation model for companies in this segment. To achieve this general objective, the goals of this applied research are:

1. Check the maturity status of Industry 4.0 in passenger rail transport through a study in the literature,
2. Explore all Industry 4.0 technologies taking them to the context of railway via semi-structured interviews with experts in the sector,
3. Organize Industry 4.0 technologies into a maturity model that demonstrates the expected benefits to improve the key productive objectives of passenger railway companies,
4. Test (hypothetically) the proposed implementation model in one of the transport operators consulted.

Throughout the study, we show the achievement of these goals using the following nomenclature. Objective one (O1) - Construct an Industry 4.0 conceptual framework based on a literature review to guide the semi-structured interviews. Objective two (O2) - Construct an Industry 4.0 opportunities framework based on the empirical findings. Objective three (O3) - Construct an Industry 4.0 maturity framework to improve the business of passenger railway companies. Objective four (O4) - Test the proposed Industry 4.0 maturity framework.

1.4 Research methods

We started with a conceptual framework (Figure 5) based on the model proposed by Frank, Dalenogare, and Ayala (2019) that suggests the four smart dimensions of Industry 4.0. Our literature review adjusted it to passenger rail transport to underpin and guide the empirical investigation (Voss et al., 2002), aiming to answer the research question.

Considering the lack of studies with the intended embracing vision, we used an exploratory and qualitative approach in an appropriate way (Goffin et al., 2019). We interviewed experts from eight transport operators and four technology providers in the Brazilian railway segment. Moreover, we used other query sources to complement the data triangulation. The proposed methodology is suitable as it provides detailed field information for an inductive theoretical construction to understand how a contemporary phenomenon happens (Yin, 2009; Eisenhardt & Graebner, 2007). The output of empirical findings was summarized in an Industry 4.0 opportunities framework (Figure 7).

We developed an Industry 4.0 maturity model for passenger railway companies (Figure 8) based on our empirical findings and the Brazilian companies' main Key Performance Indicators (KPIs). Finally, we tested the proposed framework in one of the transport operators consulted. Figure 3 shows the steps developed during the research according to the methodological procedures adopted.

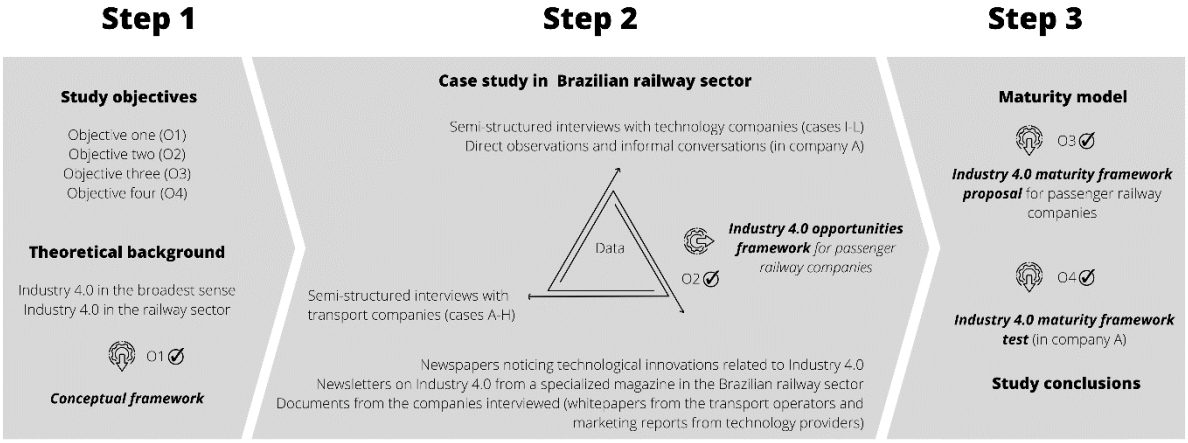

Figure 3 - Summary of the methodology procedures

1.5 Study limitations

The main limitation of this dissertation lies in the sample of companies consulted, which is restricted to Brazilian passenger railway companies, a developing country with few state-of-the-art train lines. Rail transport is related to goods and people, being the last divided into tourist trains and transport in large cities and

metropolitan areas. The present study is focused on transporting passengers using the subway and suburban trains (massive transport).

In addition, even though the proposed implementation model is extendable to other similar railway companies, we tested the maturity framework in only one of the consulted transport operators. Finally, the study analyzes the technological aspects of Industry 4.0 due to its potential to modernize the work processes of passenger railway companies and leverage the business as a whole. However, economic issues, available resources, and organizational culture must also be considered for implementing new technologies. The present study focuses on the technological aspects. The other elements are dealt with superficially.

1.6 Dissertation structure

The dissertation continues with a theoretical background in section 2, examining Industry 4.0 firstly in the broadest sense and second in the context of the railway sector. It also presents an initial conceptual framework as a starting point for empirical data collection with experts in the sector. Section 3 covers in depth the methodology procedure used in the study. Section 4 presents the results found in the cases collection, discusses them and shows an opportunities framework for Industry 4.0 in passenger rail transport. Section 5 introduces an Industry 4.0 maturity framework proposal for passenger railway companies. Section 6 shows the test of the maturity framework performed with one of the transport operators consulted. Finally, section 7 closes the study with conclusions, limitations, and suggestions for future research.

7 CONCLUSIONS

This dissertation aimed to investigate how holistically apply the Industry 4.0 concepts to passenger railway companies. We started with a conceptual framework (Figure 5) based on the model proposed by Frank, Dalenogare, and Ayala (2019) that suggests the four smart dimensions of Industry 4.0. It was adjusted after checking the maturity status of Industry 4.0 in passenger rail transport through a study in the literature. Study objective one (O1) was achieved. We proceeded through empirical research by collecting and analyzing qualitative data from cases raised with Brazilian transport operators and some technology providers in the studied segment.

The Four Smarts of Industry 4.0 (Frank, Dalenogare, & Ayala, 2019) adapted to passenger railways in our research made sense in the context of the companies consulted since we found several related front-end technologies. Our results show that Industry 4.0 can be comprehensively applied in both the internal and external dimensions of the business. The base technologies transform transport operators, connecting workers, assets, companies, and customers. Big Data is forming as the implemented or under-study technological initiatives progress. Thus, Analytics still has few applications in the sample studied. The results indicate that companies are moving towards an operational intelligence center to implement robust and efficient train offers, prescriptive maintenance, strong supply chain management, and improved passenger experience and worker performance. We propose an Industry 4.0 opportunities model for passenger railway companies (Figure 7), showing each smart dimension for passenger railways, the technology adoptions in the sample of companies consulted, and the practical implications. Study objective two (O2) was achieved.

We developed an Industry 4.0 maturity model for passenger railway companies (Figure 8) based on our empirical findings and the Brazilian companies' main KPIs. We discuss the proposed model face-to-face with specialized professionals of transport operator A to test it hypothetically. We received positive feedback that the proposed framework portrays the company's daily concerns that professionals must deal with to run the business. The consulted professionals stated that the proposed maturity stages represent a path to leverage the metrics associated with the productive objectives. For us, this showed the validity of the research constructs. Study objectives

three (O3) and four (O4) were achieved. Thus, we completed all goals listed to perform the study's general purpose, delivering two models with a holistic view of Industry 4.0 in the context of passenger railway companies.

The practical contribution of the research is to help passenger railway companies plan the Industry 4.0 journey in their segment. The proposed frameworks (Figures 7 and 8) guide companies' practices seeking business performance gains in designing new train lines and looking for more sustainable systems in operations. Companies can fit into the stages of our maturity model and pursue strategies to leverage their productive objectives by applying the proposed technologies.

The research also contributes academically to advance the overall view of Industry 4.0 as a phenomenon currently taking place, discussing published studies, and bringing empirical data from companies in the railway sector. Moreover, the dissertation delivers a significant contribution as the frameworks with this holistic view of the Fourth Industrial Revolution in the passenger railway are unprecedented.

The main limitation of this dissertation lies in the sample of companies consulted, which is restricted to Brazilian transport operators, a developing country with few state-of-the-art passenger railway lines. Another limitation is that we interviewed only one person from each transport operator, except for one company that voluntarily opted for two professionals. We understand that we have overcome this fact through a good return on validating the maturity model with expert professionals from transport operator A.

For future research, we suggest that more companies should be consulted to expand on the empirical findings. The maturity model needs to be tested in more companies in the segment. As railways from other countries are consulted, or even different modes of transport are the object of research, an expressway of study will open up. For Brazilian railway companies, we suggest joint actions such as the one reported on creating a purchasing committee of the national association ANPTrilhos. Working together, in addition to the companies sharing expertise, they will move towards the standardization and development of suppliers at a national level to support them in the technological challenges.

REFERENCES

Alawad, H., An, M., & Kaewunruen, S. (2020). Utilizing an adaptive neuro-fuzzy inference system (ANFIS) for overcrowding level risk assessment in railway stations. Applied Sciences, 10(15), 5156. https://doi.org/10.3390/app10155156

ANPTRILHOS. Como inserir os trilhos no Plano de Mobilidade (2017). Brasília, 2017. https://anptrilhos.org.br/wp-content/uploads/2017/04/WEB-Como-inserir-os-trilhos-no-Plano-de-Mobilidade.pdf

Ayala, N. F.; Paslauski, C. A., Ghezzi, A., Frank, A. G. (2017). Knowledge sharing dynamics in service suppliers' involvement for servitization of manufacturing companies. International Journal of Production Economics, Volume 193, 2017, Pages 538-553. https://doi.org/10.1016/j.ijpe.2017.08.019

Barreto, L., Amaral, A., Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. Procedia Manufacturing, Volume 13, 2017, Pages 1245-1252. https://doi.org/10.1016/j.promfg.2017.09.045

Besinovic, N., De Donato, L., Flammini, F., Goverde, R. M. P., Lin, Z., Liu, R., Marrone, S., Nardone, R., Tang, T., Vittorini, V. (2021). Artificial Intelligence in Railway Transport: Taxonomy, Regulations, and Applications. In IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 9, pp. 14011-14024, Sept. 2022, doi: 10.1109/TITS.2021.3131637.

Bueno, A., Filho, M. G., Frank A. G. (2020). Smart production planning and control in the Industry 4.0 context: A systematic literature review, Computers & Industrial Engineering, Volume 149, 2020, 106774. https://doi.org/10.1016/j.cie.2020.106774

Bustos, A., Rubio, H., Soriano-Heras, E., Castejon, C. (2021). Methodology for the integration of a high-speed train in Maintenance 4.0. Journal of Computational Design and Engineering, Volume 8, Issue 6, December 2021, Pages 1605–1621, https://doi.org/10.1093/jcde/qwab064

CER, C., & EIM, U. (2016). A Roadmap for Digital Railways. https://uic.org/com/IMG/pdf/a_roadmap_for_digital_railways.pdf

Consilvio, A., Sanetti, P., Anguìta, D., Crovetto, C., Dambra, C., Oneto, L., Papa, F., Sacco, N. (2019). "Prescriptive Maintenance of Railway Infrastructure: From Data Analytics to Decision Support," 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Cracow, Poland, 2019, pp. 1-10, doi: 10.1109/MTITS.2019.8883331

Corman, F., D'Ariano, A., Marra, A. D., Pacciarelli, D., Samà, M. (2017). Integrating train scheduling and delay management in real-time railway traffic control. Transportation Research Part E: Logistics and Transportation Review, Volume 105, 2017, Pages 213-239. https://doi.org/10.1016/j.tre.2016.04.007

Corman, F., Kecman, P. (2018). Stochastic prediction of train delays in real-time using Bayesian networks. Transportation Research Part C: Emerging Technologies, Volume 95, 2018, Pages 599-615. https://doi.org/10.1016/j.trc.2018.08.003

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. International Journal of Production Economics, Volume 204, 2018, Pages 383-394. https://doi.org/10.1016/j.ijpe.2018.08.019

Dornelles, J. de A., Ayala, N.F., Frank., A.G. (2022). Smart working in Industry 4.0: How digital technologies enhance manufacturing workers' activities. Computers & Industrial Engineering, 163 (2022). https://doi.org/10.1016/j.cie.2021.107804

Eisenhardt, K. M., Graebner, M. E., 2007. Theory building from cases: opportunities and challenges. Acad. Manag. J. 50, 25–32. http://dx.doi.org/10.2307/20159839

Fourie, C. J. and Chimusoro, O., 2018. An examination of the relationship between supply chain management practices and business performance: A case analysis of a passenger rail company. South African J. Ind. Eng., vol. 29, no. 2, pp. 141–152, 2018. https://hdl.handle.net/10520/EJC-10bf56a695

Frank, A. G., Dalenogare, L. S., Ayala, N. F. (2019a). Industry 4.0 Technologies: Implementation Patterns in Manufacturing Companies. International Journal of Production Economics 210: 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

Frank, A. G., Mendes, G. H.S., Ayala, N. F., Ghezzi, A. (2019b). Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. Technological Forecasting and Social Change, Volume 141, 2019, Pages 341-351. https://doi.org/10.1016/j.techfore.2019.01.014

Frederico, G.F., Garza-Reyes, J.A., Anosike, A., & Kumar, V. (2020). Supply Chain 4.0: concepts, maturity and research agenda. Supply Chain Management, Vol. 25 No. 2, pp. 262-282. https://doi.org/10.1108/SCM-09-2018-0339

Gerhátová, Z., Zitrický, V., Klapita, V. (2021a). Industry 4.0 Implementation Options in Railway Transport. Transportation Research Procedia, Volume 53, Pages 23-30. https://doi.org/10.1016/j.trpro.2021.02.003

Gerhátová, Z., Zitrický, V. Gašparik, J. (2021b). Analysis of Industry 4.0 elements in the transport process at the entrance of the train from Ukraine to Slovakia. Transportation Research Procedia, Volume 55, Pages 165-171. https://doi.org/10.1016/j.trpro.2021.06.018

Ghofrani, F., He, Q., Goverde, R. M. P., Liu, X. (2018). Recent applications of big data analytics in railway transportation systems: A survey. Transportation Research Part C: Emerging Technologies, Volume 90, 2018, Pages 226-246, https://doi.org/10.1016/j.trc.2018.03.010

Goffin, K., Åhlström, P., Bianchi, M., & Richtnér, A. (2019). Perspective: State-of-the-Art: The Quality of Case Study Research in Innovation Management. Journal of Product Innovation Management, 36(5), 586–615. https://doi.org/10.1111/jpim.12492

Huang, P., Wen, C., Fu, L., Peng, Q., Tang, Y. (2020). A deep learning approach for multi-attribute data: A study of train delay prediction in railway systems. Information Sciences, Volume 516, 2020, Pages 234-253. https://doi.org/10.1016/j.ins.2019.12.053

Hussin, A. A. (2018). Education 4.0 Made Simple: Ideas for Teaching. International Journal of Education & Literacy Studies. http://dx.doi.org/10.7575/aiac.ijels.v.6n.3p.92

Ivanov, D., Dolgui, A., & Sokolov, B. (2018). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. Internationalc Journal of Production Research. https://doi.org/10.1080/00207543.2018.1488086

Ivanov, D., Dolgui, A. (2020). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Production Planning & Control. https://doi.org/10.1080/09537287.2020.1768450

Jo, O., Kim, Y.-K., Kim, J. (2018). Internet of Things for Smart Railway: Feasibility and Applications. In IEEE Internet of Things Journal, vol. 5, no. 2, pp. 482-490, April 2018, doi: 10.1109/JIOT.2017.2749401

Kagermann, H., Wahlster, W., Helbig, J. (2013). Recommendations for Implementing the Strategic Initiative Industrie 4.0: Securing the Future of German Manufacturing Industry. Final Report of the Industrie 4.0 Working Group. Acatech, Forschungsunion.

Kans, M., Galar, D., Thaduri, A. (2016). Maintenance 4.0 in Railway Transportation Industry. In: , et al. Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015). Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-319-27064-7_30

Karakose, M., Yaman, O. (2020). Complex Fuzzy System Based Predictive Maintenance Approach in Railways. in IEEE Transactions on Industrial Informatics, vol. 16, no. 9, pp. 6023-6032, Sept. 2020. doi: 10.1109/TII.2020.2973231

Kusiak, A. (2018). Smart manufacturing. International Journal of Production Research, 56:1-2, 508-517. https://doi.org/10.1080/00207543.2017.1351644

Laifa, H., Khcherif, R., Ghezalaa, H. H. B. (2021). Train delay prediction in Tunisian railway through LightGBM model. Procedia Computer Science, Volume 192, 2021, Pages 981-990. https://doi.org/10.1016/j.procs.2021.08.101

Laiton-Bonadiez, C., Branch-Bedoya, J., Zapata-Cortes, J., Paipa-Sanabria, E., Arango-Serna, M. (2022). Industry 4.0 Technologies Applied to the Rail Transportation Industry: A Systematic Review. Sensors, 22, 2491. https://doi.org/10.3390/s22072491

Li, Q. Y., Zhong, Z. D., Liu, M., Fang, W. W. (2017). Chapter 14 - Smart Railway Based on the Internet of Things, Editor(s): Hui-Huang Hsu, Chuan-Yu Chang, Ching-Hsien Hsu, In Intelligent Data-Centric Systems, Big Data Analytics for Sensor-Network Collected Intelligence, Academic Press, 2017, Pages 280-297, https://doi.org/10.1016/B978-0-12-809393-1.00014-3

Liao, Y., Deschamps, F., Loures, E.D.F.R., Ramos, L.F.P. (2017). Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. International Journal of Production Research, 55:12, 3609-3629. https://doi.org/10.1080/00207543.2017.1308576

Liu, P., Schmidt, M., Kong, Q., Wagenaar, J. C., Yang, L., Gao, Z., Zhou, H. (2020). A robust and energy-efficient train timetable for the subway system. Transportation Research Part C: Emerging Technologies, Volume 121, 2020, 102822. https://doi.org/10.1016/j.trc.2020.102822

Lom, M., Pribyl, O., Svitek, M. (2016). Industry 4.0 as a part of smart cities. Smart Cities Symposium Prague (SCSP), pp. 1-6. doi: 10.1109/SCSP.2016.7501015

Meindl, B., Ayala, N. F., Mendonça, J., Frank, A. G. (2021). The Four Smarts of Industry 4.0: Evolution of ten Years of Research and Future Perspectives. Technological Forecasting and Social Change 168: 120784. https://doi.org/10.1016/j.techfore.2021.120784

Mulongo, N. Y.; Mnkandla, E., Kanakana-Katumba, G. (2021). Artificial Intelligence as Key Driver for Competitiveness in the Railway Industry: Review. 2021 62nd International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS), pp. 1-6, doi: 10.1109/ITMS52826.2021.9615314

Nair, R., Hoang, T. L., Laumanns, M., Chen, B., Cogill, R., Szabó, J., Walter, T. (2019). An ensemble prediction model for train delays. Transportation Research Part C: Emerging Technologies, Volume 104, 2019, Pages 196-209. https://doi.org/10.1016/j.trc.2019.04.026

Oneto, L., Fumeo, E., Clerico, G., Canepa, R., Papa, F., Dambra, C., Mazzino, N., Anguita, D. (2017). Dynamic Delay Predictions for Large-Scale Railway Networks: Deep and Shallow Extreme Learning Machines Tuned via Thresholdout. in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 47, no. 10, pp. 2754-2767, Oct. 2017. doi: 10.1109/TSMC.2017.2693209

Oneto, L., Fumeo, E., Clerico, G., Canepa, R., Papa, F., Dambra, C., Mazzino, N., Anguita, D. (2018). Train Delay Prediction Systems: A Big Data Analytics Perspective. Big Data Research, Volume 11, 2018, Pages 54-64. https://doi.org/10.1016/j.bdr.2017.05.002

Pieriegud, J. (2018). Digital Transformation of Railways. SGH Warsaw School of Economics, Siemens. https://rail-research.europa.eu/wp-content/uploads/2018/04/DIGITAL_TRANSFORMATION_RAILWAYS_2018_web.pdf

Rocha, A., Araújo, A., Carvalho, A., Sepulveda, J. (2018). A New Approach for Real Time Train Energy Efficiency Optimization. Energies 2018, 11(10), 2660. https://doi.org/10.3390/en11102660

Romero, D., Stahre, J., Taisch, M. (2020). The Operator 4.0: Towards socially sustainable factories of the future. Computers & Industrial Engineering, Volume 139, 2020, 106128. https://doi.org/10.1016/j.cie.2019.106128

Scheffer, S., Martinetti, A., Damgrave, R., van Dongen, L., 2021. Augmented reality for IT/OT failures in maintenance operations of digitized trains: current status, research challenges and future directions. Procedia CIRP, Volume 100, Pages 816-821. https://doi.org/10.1016/j.procir.2021.05.038

Schuh, G., Anderl, R., Dumitrescu, R., Krüger, A., & Hompel, M. ten. (2020). Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies – UPDATE 2020 – (acatech STUDY). https://en.acatech.de/publication/industrie-4-0-maturity-index-update%202020/

Shao, X.F., Liu, W., Li, Y., Chaudhry, H.R., Yue, X.G. (2021). Multistage implementation framework for smart supply chain management under industry 4.0. Technological Forecasting and Social Change 162. https://doi.org/10.1016/j.techfore.2020.120354

Tabim, V.M., Ayala, N.F., & Frank, A.G. (2021). Implementing Vertical Integration in the Industry 4.0 Journey: Which Factors Influence the Process of Information Systems Adoption? Inf Syst Front (2021). https://doi.org/10.1007/s10796-021-10220-x

Takikawa, M. (2016). Innovation in railway maintenance utilizing information and communication technology (smart maintenance initiative). Japan Railway & Transport Review, 67, 14.

Tang, R.; De Donato, L.; Besinović, N.; Flammini, F.; Goverde, R.M.; Lin, Z.; Liu, R.; Tang, T.; Vittorini, V.; Wang, Z. (2022). A literature review of Artificial Intelligence applications in railway systems. Transportation Research Part C: Emerging Technologies, Volume 140, 103679. https://doi.org/10.1016/j.trc.2022.103679

Thaduri, A., Galar, D., Kumar, U., 2015. Railway assets: a potential domain for big data analytics. Procedia Comput. Sci., 53 (2015), pp. 457-467. https://doi.org/10.1016/j.procs.2015.07.323

Tortorella, G. L., Fogliatto, F. S., Vergara, A. M. C., A., Vassolo, R., Sawhney, R. (2019). Healthcare 4.0: trends, challenges and research directions. Production Planning & Control, 31:15, 1245-1260. https://doi.org/10.1080/09537287.2019.1702226

Voss, C.A., Tsikriktsis, N., Frohlich, M., 2002. Case research in operations management. Int. J. Oper. Prod. Manag. 22, 195–219. http://dx.doi.org/10.1108/

Wang, Y., Zhu, S., D'Ariano, A., Yin, J., Miao, J., Meng, L. (2021). Energy-efficient timetabling and rolling stock circulation planning based on automatic train operation levels for metro lines. Transportation Research Part C: Emerging Technologies, Volume 129, 2021, 103209, https://doi.org/10.1016/j.trc.2021.103209

Xu, L. D., Xu, E. L., Li, L. (2018). Industry 4.0: state of the art and future trends. International Journal of Production Research, 56:8, 2941-2962. https://doi.org/10.1080/00207543.2018.1444806

Yin, R. K. (2009). Case Study Research: Design and Methods (4th ed.). Sage Publications, Inc.

Yokoyama, A. (2015). Innovative Changes for Maintenance of Railway by Using ICT–To Achieve “Smart Maintenance”. Procedia CIRP, Volume 38, 2015, Pages 24-29. https://doi.org/10.1016/j.procir.2015.07.074

APPENDIX A - INVITATION TO PARTICIPATE IN RESEARCH

Pesquisador: Michael Luciano Chaves Franz, Engenheiro metroferroviário

Perfil profissional https://www.linkedin.com/in/mlchavesfranz/

Orientador: Néstor Fabián Ayala, Professor e pesquisador

Perfil profissional https://www.linkedin.com/in/nestor-fabian-ayala/

1. Justificativa e problema de pesquisa

A tecnologia ferroviária acompanhou o progresso das revoluções industriais, desde a criação da locomotiva a vapor no século XIX, substituindo a tração animal, até o surgimento dos trens de alta velocidade em meados do século XX. A literatura envolvendo o tema Indústria 4.0 e ferrovias ainda precisa ser explorada. Na prática, há mais iniciativas de aplicações tecnológicas isoladas. Não se percebe uma visão integrada de como implementar as tecnologias da quarta revolução industrial na ferrovia. Englobando as dimensões internas e externas do negócio. Diante disso, esta pesquisa levanta uma importante questão: Como os conceitos da Indústria 4.0 podem ser aplicados ao transporte ferroviário de passageiros em uma visão holística? De forma que auxilie operadoras metroferroviárias a iniciarem o planejamento da sua jornada rumo à Indústria 4.0 para melhorar de forma geral o desempenho das empresas.

2. Objetivo da pesquisa

A presente pesquisa tem por objetivo geral avaliar como os conceitos da Indústria 4.0 podem ser aplicados de forma holística nas transportadoras de passageiros sobre trilhos. Os objetivos específicos são: verificar o estado de maturidade da Indústria 4.0 no transporte sobre trilhos através de estudo na literatura; explorar todas as tecnologias da Indústria 4.0 que poderiam ser aplicadas levando-as ao contexto do transporte sobre trilhos via profissionais especialistas; organizar as tecnologias em um modelo de maturidade de Indústria 4.0 visando melhorar os principais objetivos produtivos das operadoras metroferroviárias de acordo com seus indicadores de desempenho; testar (hipoteticamente) o modelo de implementação proposto em uma das empresas consultadas.

3. Como participar da pesquisa

Se você é um profissional do transporte de passageiros sobre trilhos ou das empresas fornecedoras de tecnologia para este segmento, que esteja utilizando, implementado ou estudando tecnologias *smart* (digitalização de processos, conectividade, uso massivo de dados, análises em tempo real), e que esteja disposto a colaborar com esta pesquisa, você será bem-vindo a contribuir nesse projeto.

Você participará de uma entrevista em ambiente virtual com duração de aproximadamente 40-60 min, com questões abertas, ficando à vontade para responder e explicar os cases da sua empresa. As entrevistas serão gravadas para fins de consultas posteriores e para uso nos resultados da pesquisa, com sigilo de nomes de profissionais e de empresas. Apenas

será dito que são profissionais especialistas do transporte sobre trilhos do Brasil ou de empresas fornecedoras de tecnologias.

Desde já, agradecemos por sua disposição em colaborar, que certamente contribuirá para o desenvolvimento das operadoras de transporte sobre trilhos, em especial, as de passageiros do Brasil.

4. Questionário para a entrevista semiestruturada

O caminho a ser percorrido para chegar na Indústria 4.0 passa pela implementação das tecnologias de base (IoT, Cloud Computing, Big Data, e Analytics). Estas tecnologias são responsáveis pela transformação digital da empresa, e servem de suporte às tecnologias front-end responsáveis por empoderar a companhia em suas dimensões internas (Smart Operation e Smart Working) e externas (Smart Supply Chain e Smart Service). O framework inicial de pesquisa que segue (Figura 1) é proposto para guiar as entrevistas com os profissionais especialistas.

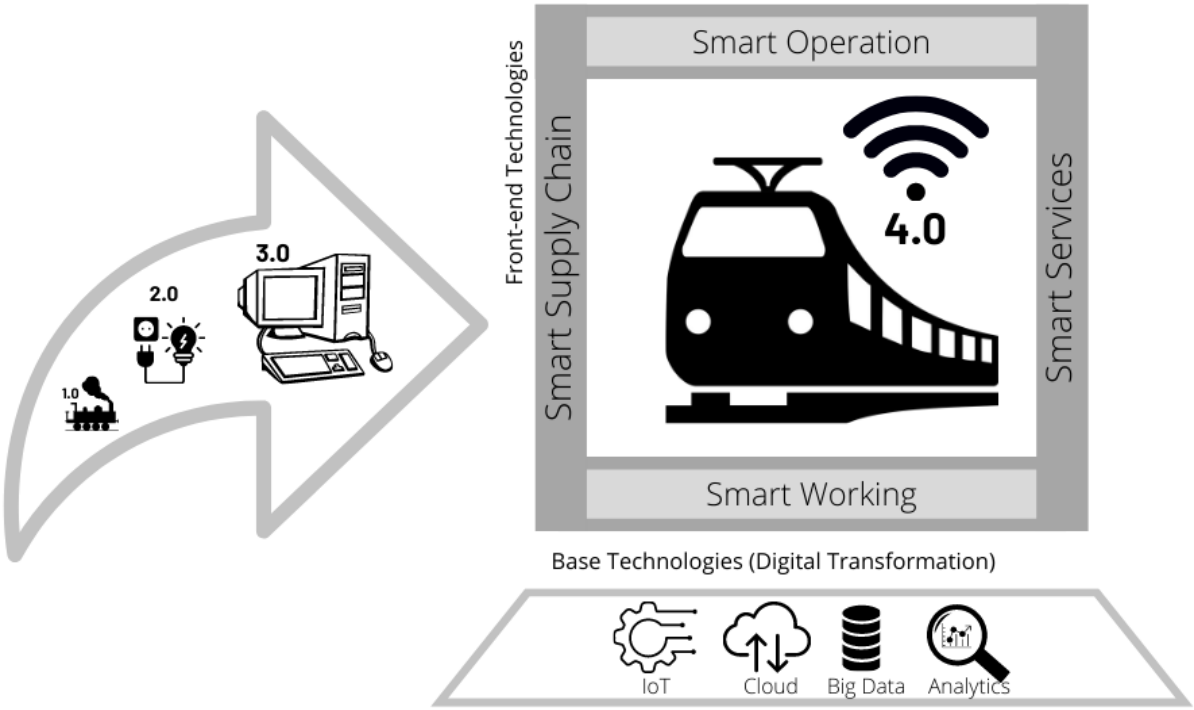

Figura 1 - Framework inicial de pesquisa para coleta de dados empíricos

A entrevista percorrerá as quatro dimensões *smart* da Indústria 4.0 adaptadas com suas particularidades para o transporte sobre trilhos. Na oportunidade, serão ouvidos os casos de implementação ou em estudo das tecnologias conforme quadro a seguir.

DIMENSÃO	SMART OPERATION	SMART WORKING	SMART SUPPLY CHAIN	SMART SERVICES
DESCRIÇÃO	Tecnologias que auxiliam no gerenciamento do fluxo de trens e dos recursos nas estações de passageiros, na redução do consumo energético, na gestão da manutenção dos ativos, na segurança operacional e patrimonial.	Tecnologias que auxiliam os trabalhadores nas suas atividades, dando-lhes suporte físico e cognitivo, aliviando-lhes do esforço excessivo, proporcionando-lhes informações úteis e suporte nas atividades, maior conforto e possibilidades de capacitação.	Tecnologias para integração horizontal das operadoras com seus fornecedores de materiais e serviços, ou até mesmo entre operadoras a fim de aquisições ou contratações conjuntas, melhoria dos níveis de estoque e do fluxo de materiais no almoxarifado.	Tecnologias para prestação de um serviço de transporte com maior qualidade percebida pelos passageiros, ofertas de serviços adicionais nas estações e trens, melhor aproveitamentos dos espaços, uso dos dados dos usuários para alavancar o negócio.
TECNOLOGIAS ENVOLVIDAS	- Sensores, atuadores, CLP, SCADA, MES, e ERP para integração vertical; - Simulação de processos e comissionamento virtual; - Robôs (industriais, veículos guiados autonomamente), comunicação M2M, identificação automática de não conformidades; - Identificação e rastreabilidade de matérias-primas e outros; - Flexibilidade para atendimento aos clientes; - Monitoramento e melhoria do consumo energético.	- Exoesqueletos e robôs colaborativos; - Realidade aumentada e virtual; - Assistentes habilitados por voz; - Gêmeo digital; - Visão computacional e analítica; - Sistemas de suporte à decisão; - Inteligência artificial; - Dispositivos vestíveis; - Automação de tarefas; - Sensores de máquinas e do meio ambiente; - Rede social empresarial.	- Plataformas digitais com fornecedores; - Plataformas digitais com outras empresas do grupo; - Manufatura aditiva; - RFID e sistemas de rastreamento; - Realidade aumentada e *smart glasses*; - Veículos guiados automaticamente (AGV) e robôs móveis autônomos (AMR); - Algoritmos para simulação e otimização.	- Plataformas digitais com clientes; - Melhoras na experiência do usuário; - Serviços digitais e conectividade; - Informações em tempo real; - Infoentretenimento; - Sistemas de bilhetagem automática, integrações.

APPENDIX B - INVITATION TO PARTICIPATE IN RESEARCH (ENGLISH)

Researcher: Michael Luciano Chaves Franz, Railway engineer

Professional profile https://www.linkedin.com/in/mlchavesfranz/

Advisor: Néstor Fabián Ayala, Professor and researcher

Professional profile https://www.linkedin.com/in/nestor-fabian-ayala/

1. Justification and research problem

Railway technology has followed the progress of industrial revolutions, from creating the steam locomotive in the 19th century, replacing animal traction, and consecrating the horsepower unit measurement, to the emergence of high-speed trains in the mid-20th century). Although, the literature involving the theme of Industry 4.0 and railways still needs to be explored. In practice, there are more initiatives of technology applications isolated. As far as we know, there is no integrated vision for systematically implementing Industry 4.0 in the railway considering all business dimensions. Given this, we raise an important question: How can the Industry 4.0 concepts be applied holistically to passenger rail transport? To help passenger railway companies plan their journey towards Industry 4.0 to improve their performance.

2. Research purpose

The present research has the general objective of evaluating how the concepts of Industry 4.0 can be applied in a holistic way in passenger railway companies. The specific goals are: to check the maturity status of Industry 4.0 in passenger rail transport through a study in the literature, explore all Industry 4.0 technologies by taking them to the context of railway via interviews with experts in the sector, organize Industry 4.0 technologies into a maturity model that demonstrates the expected benefits to improve the main productive objectives of passenger railway companies according to their KPIs, test (hypothetically) the proposed implementation model in one of the transport operators consulted.

3. How to participate in the research

Suppose you are a passenger railway company professional or one of the companies that supply technology for this segment, who are using, implementing, or studying smart technologies (digitization of processes, connectivity, massive use of data, real-time analysis), that you are willing to collaborate with this research. In that case, you are welcome to contribute to this project.

You will participate in an interview in a virtual environment lasting approximately 40-60 minutes, with open questions, feeling free to respond and explain your company's cases. The interviews will be recorded for later consultation and use in the research results, with the confidentiality of the names of professionals and companies. It will only be said that they are specialists in the Brazilian passenger railway companies or technology supply companies.

Thank you in advance for your willingness to collaborate, which will certainly contribute to the development of railway companies, especially those for passengers in Brazil.

4. Questionnaire for the semi-structured interview

The path to Industry 4.0 involves implementing base technologies (IoT, Cloud Computing, Big Data, and Analytics). These technologies are responsible for the company's digital transformation and support the front-end technologies accountable for empowering the company in its internal dimensions (Smart Operation and Smart Working) and external dimensions (Smart Supply Chain and Smart Services). The initial research framework that follows (Figure 1) focused on the passenger railway companies is proposed for conducting the interviews.

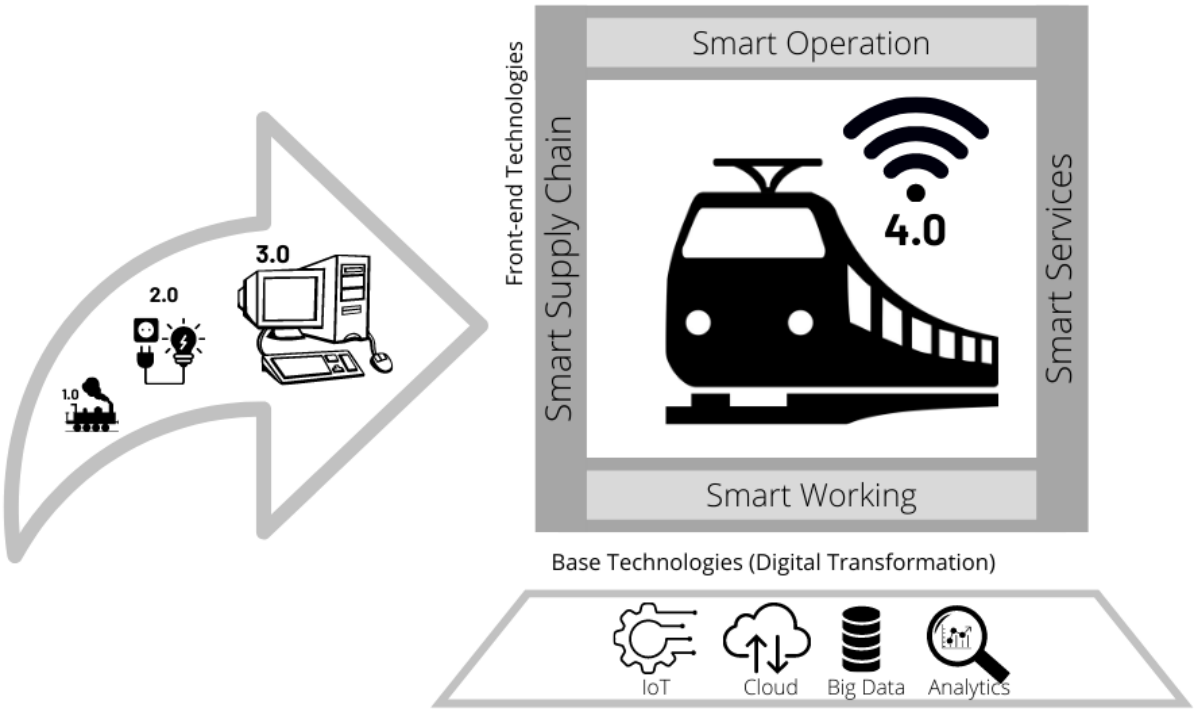

Figure 1 - Initial research framework for empirical data collection

The interview will cover the four smart dimensions of Industry 4.0 adapted with their particularities for passenger rail transport. On that occasion, cases of implementation or study of technologies, as shown in the table below, will be heard.

DIMENSION	SMART OPERATION	SMART WORKING	SMART SUPPLY CHAIN	SMART SERVICES
DESCRIPTION	Technologies that help manage the flow of trains and resources at passenger stations, to reduce energy consumption, manage asset maintenance, operational safety and security.	Technologies that help workers in their activities, give them physical and cognitive support, relieve them of excessive effort, provide them with useful information and support in activities, and provide greater comfort and training possibilities.	Technologies for horizontal integration of transport operators with their suppliers of materials and services, or even between transport operators for acquisitions or joint contracts, improvement of inventory levels, and the flow of materials in the warehouse.	Technologies for providing a transport service with higher quality perceived by passengers, offers of additional services at stations and trains, better use of spaces, and use of customer data to leverage the business.
RELATED TECHNOLOGIES	- Sensors, actuators, PLC, SCADA, MES, and ERP to vertical integration, - Process simulation and virtual commissioning, - Industrial robots, M2M communication, automatic nonconformities identification, - Sensors for raw materials and others, - Flexibility in customer service, - Energy monitoring and energy efficiency improving systems.	- Exoskeletons, collaborative robots, - Virtual and augmented reality, - Voice-enabled assistants, - Digital twin, - Computer vision and visual analytics, - Smart decision support system, - Artificial intelligence, - Wearable devices, - Tasks automation, - Environment and machine sensors, - Industrial social networks.	- Digital platforms with other company units, - Digital platforms with suppliers, - Additive manufacturing, - Tracking and tracing systems, - Augmented reality and smart glasses, - Automated guided vehicles (AGV) and autonomous mobile robots (AMR), - Algorithms for simulation and optimization.	- Digital platforms with customers, - Improvements in the customer experience, - Digital services and connectivity, - Information in real-time, - Infotainment, - Automatic ticketing systems and integrations.

APPENDIX C - SCRIPT OF INTERVIEWS

Perfis do entrevistador e entrevistado(s):

- Apresentação da pesquisa e do entrevistador;
- Apresentação do(s) entrevistado(s) e da empresa;

***Smart Operation*:**

1) Existe algum monitoramento do fluxo de passageiros nas estações e no interior dos trens? O que se pode fazer com os dados gerados? Existe alguma flexibilidade no atendimento aos clientes?
2) Existe alguma plataforma de simulação para planejamento da oferta de trens? Que busque equilíbrio entre atendimento da demanda de passageiros e consumo de energia. Quais variáveis são consideradas?
3) Qual o nível de automação da operação de trens na sua empresa? Há outros processos automatizados, com uso de robôs, M2M, ou identificação automática de não conformidades, por exemplo?
4) Existe um monitoramento do consumo energético e ações para melhoria da eficiência energética?
5) Quais ativos são monitorados em tempo real? O que se pode fazer com os dados gerados? Existe alguma plataforma de manutenção preditiva em uso na empresa?

***Smart Working*:**

6) Como as tecnologias têm auxiliado nos processos de trabalho da sua empresa? Como prover suporte físico e/ou cognitivo aos trabalhadores.
7) Há uso de dispositivos móveis nas atividades para consulta de informações úteis? Documentos como procedimentos, diagramas ou desenhos.
8) Há suporte aos trabalhadores nas suas atividades com uso de recursos de som e imagem, plataformas ou aplicativos?
9) Há iniciativas de capacitação e desenvolvimento com uso de recursos tecnológicos?

***Smart Supply Chain*:**

10) Existe alguma plataforma de integração horizontal da empresa com seus fornecedores de materiais ou serviços?
11) E com empresas do mesmo grupo acionista? Há oportunidade de ganhos de escala em aquisições ou contratações conjuntas com elas?

12) Como o almoxarifado é afetado por tecnologias de automação, rastreabilidade de materiais, manufatura aditiva?

13) Como lidam com as necessidades de peças de reposição dos ativos, níveis de estoque? Há suporte tecnológico para isso?

***Smart Services*:**

14) Existe algum Aplicativo da sua empresa disponível aos clientes? O que se pode obter nele?

15) Existe alguma iniciativa digital de venda de bilhetes? Cobrança de ticket proporcional ao deslocamento?

16) Como as informações chegam aos passageiros nas estações e trens? São emitidos avisos sonoros e/ou visuais em tempo real? Há rede de internet disponível aos clientes?

17) Os clientes são atendidos em tempo real com auxílio de plataformas ou redes sociais?

18) Como os dados dos passageiros são utilizados para alavancar o negócio? Há suporte tecnológico para isso?

APPENDIX D - SCRIPT OF INTERVIEWS (ENGLISH)

Interviewer and interviewee(s) profiles:

- Presentation of the research and the interviewer,
- Presentation of the interviewee(s) and the company.

Smart Operation:

1) Is there any passenger flow monitoring at the stations and inside the trains? What can you do with the generated data? Is there any flexibility in customer service?
2) Is there any simulation platform to prepare the train offer program? Seeking a balance between meeting passenger demand and energy consumption. Which variables are considered?
3) What is the level of automation of train operation in your company? Are there other automated processes using robots, M2M, or automatic non-conformity identification?
4) Is there energy consumption monitoring and actions to improve energy efficiency?
5) Which assets are monitored in real-time? What can you do with the generated data? Is there any predictive maintenance platform in use in the company?

Smart Working:

6) How have technologies helped your company's work processes? How to provide physical or cognitive support to workers.
7) Are mobile devices used in activities to consult useful information? Documents such as procedures, diagrams, or drawings.
8) Is there support for workers in their activities using sound and image resources, platforms, or applications?
9) Are there training and development initiatives using technological resources?

Smart Supply Chain:

10) Is there any horizontal integration platform for the company with its suppliers of materials or services?
11) And with companies of the same shareholder group? Are there opportunities for scale gains in acquisitions or joint contracts with them?
12) How is the warehouse affected by automation technologies, material traceability, and additive manufacturing?

13) How do you deal with asset spare parts needs and inventory levels? Are there technology initiatives supporting this?

Smart Services:

14) Is there any App from your company available to customers? What can you get from it?

15) Is there any digital ticket sales initiative? Is ticket charge proportional to displacement?

16) How does information reach passengers at stations and trains? Are sound or visual warnings issued in real-time? Is there an internet network available to customers?

17) Are customers served in real-time using platforms or social networks?

18) How are passenger data used to leverage the business? Are there technology initiatives supporting this?